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TOPICAL REPORT

ELECTROCHEMICAL ENERGY STORAGE FOR AN ORBITING SPACE STATION

BY

R. E. MARTIN

DECEMBER 1981

UNITED TECHNOLOGIES CORPORATION
POWER SYSTEMS DIVISION



PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NO. NAS3-21293
TASK I - STATE-OF-THE-ART ASSESSMENT AND PERFORMANCE MODEL

NASA- LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135
DR. MARGARET A. REID, PROJECT MANAGER

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FOREWORD

This topical report summarizes the results of a feasibility study of an Electrochemical Energy Storage System for a Large Orbiting Space Station based upon alkaline electrolyte cell technology. The study was conducted for the National Aeronautics and Space Administration - Lewis Research Center under Contract No. NAS3-21293, Task 1, State-of-the-Art Assessment and Performance Model from 1 August 1980 through 28 February 1981.

The NASA Project Manager for this contract was Dr. Margaret A. Reid. The contributions of Dr. Reid and other members of the Electrochemistry Branch Staff at NASA-Lewis are gratefully acknowledged.

The study was conducted by Mr. R. E. Martin, who was the Project Manager for Power Systems Division. Computer programming assistance was provided by Mr. L. S. Rec.

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ABSTRACT

A study was conducted to define the system weight of a multi-hundred kilowatt fuel cell-electrolysis cell energy storage system based upon alkaline electrochemical cell technology for use in a future orbiting space station in low earth orbit (LEO). The study identifies a preliminary system conceptual design, fuel cell module performance characteristics, subsystem and system weights, and overall system efficiency.

The impact of fuel cell module operating temperature and efficiency upon energy storage system weight was investigated. The electrolysis cell system operating temperature and pressure for the study was 180°F (82.2°C) and 200 psia (138.0 N/cm²), respectively. The weight of an advanced technology system featuring high strength filament wound reactant tanks and a fuel cell module employing light-weight graphite electrolyte reservoir plates was defined.

The high performance of the alkaline fuel cell results in a baseline 100 kW fuel cell-electrolysis cell energy storage system including solar array, space radiator, reactant storage tanks and power conditioner weight at a 140°F (60°C) fuel cell module operating temperature of 15,732 lbs (7,136 kg). The energy storage portion of the system, that is, the fuel cell module, the electrolysis cell module, reactants and tanks has an energy storage density of 55.8 watt-hours/lb (123 watt-hours/kg) which includes sufficient reactant storage for a 2-hour emergency operation of the fuel cell module.

An advanced technology 100 kW energy storage system weighs 13,779 lbs (6,250 kg). Similarly, the energy storage portion of the advanced technology system has an energy storage density of 91.4 watt-hours/lb (201 watt-hours/kg).

I. SUMMARY

This topical report summarizes the results of a feasibility study to establish the potential of the alkaline electrolyte fuel cell as the power source in an energy storage system for space application. Power levels of 35 kW to 250 kW in low earth orbit are considered.

Scope

The study identified fuel cell system and electrolysis cell system performance characteristics, a preliminary system conceptual design, system weight and efficiency. As part of the study, alkaline fuel cell technology goals were identified and an alkaline fuel cell performance prediction was established.

Results

A computer math model was developed to assist in defining subsystem weights of the fuel cell-electrolysis cell energy storage system. The total system weight of a 100 kW baseline fuel cell-electrolysis cell energy storage system was 15,732 lbs (7,136 kg). The energy storage portion of the system, that is, the fuel cell module, electrolysis cell module, reactants and tanks, has an energy storage density of 55.8 watt-hours/lb (123 watt-hours/kg). The fuel cell system is based upon the Power Systems Division developed fuel cell powerplants delivered to the Navy and NASA.

The total system weight of a 100 kW advanced technology fuel cell-electrolysis cell energy storage system was 13,779 lbs (6,250 kg). Similarly, the energy storage portion of the advanced technology system has an energy storage density of 91.4 watt-hours/lb (201 watt-hours/kg). The fuel cell system features a power section with lightweight graphite electrolyte reservoir plates.

II. INTRODUCTION

Background

United Technologies Corporation has maintained an active program of fuel cell research, development, production and delivery since 1959.

The activity includes fuel cells which use phosphoric acid or molten carbonate electrolyte and fuel cells which use an alkaline electrolyte.

The fuel cells which use phosphoric acid or molten carbonate electrolyte are designed for ground application for utility, commercial, and military applications. These powerplants operate on a variety of hydrocarbon fuels, such as methanol, naphtha, JP-4, natural gas, and gas derived from coal gasification. These powerplants include inverters to convert the DC power generated by the fuel cells to AC power at voltages and frequencies required by the specific application. Power levels range from 1.5 kW for Army ground power to 4.8 megawatts for utility demonstrator powerplants now under construction in New York City and Japan. The molten carbonate technology is being developed for large utility power station operation on fuel derived from coal gasification.

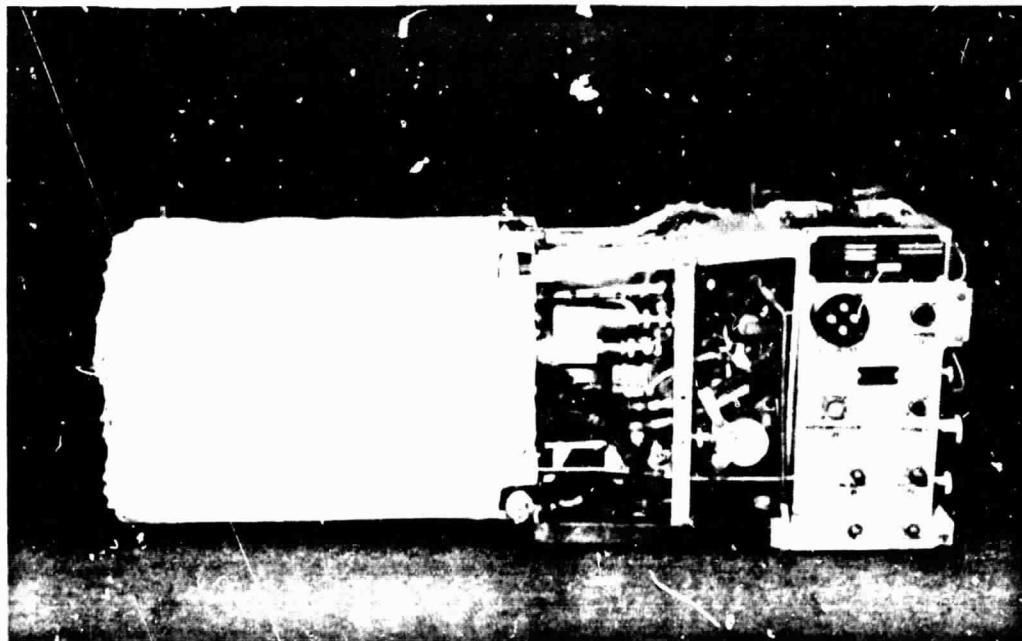
The alkaline electrolyte fuel cells operate on hydrogen and oxygen and have been developed for aerospace and undersea applications. The culmination of twenty-two years of research and development are the 12 kW fuel cell powerplant, shown in Figure 1, for the Space Shuttle Orbiter and the 30 kW unit, Figure 2, for the U.S. Navy.

The development history of alkaline electrolyte fuel cells and the technology advances from on-going technology programs sponsored by NASA at United Technologies Corporation is presented in the Appendix.

Power Systems Division

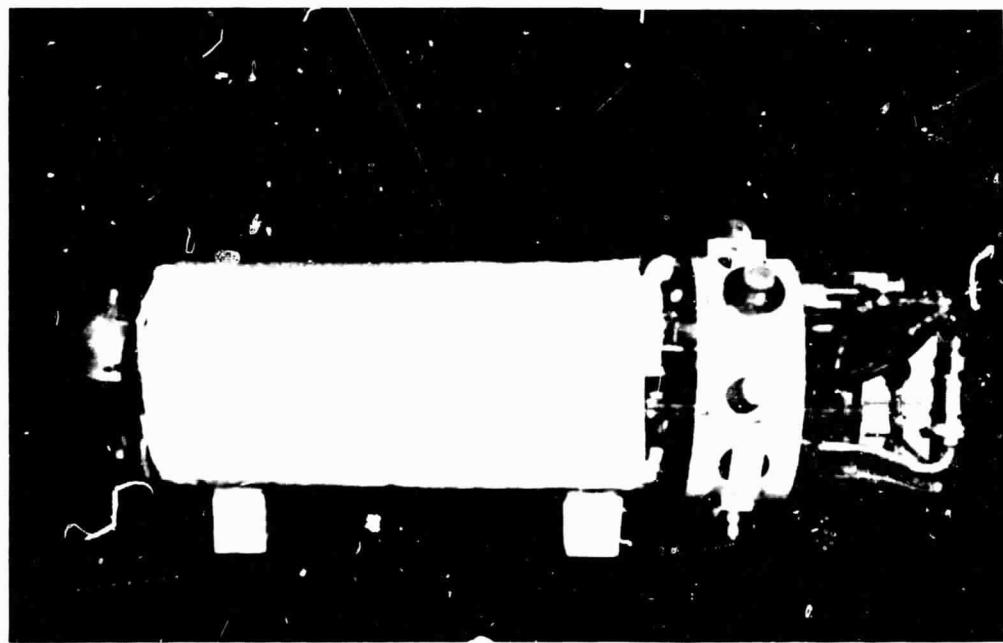
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Figure 1. Orbiter Fuel Cell Powerplant



(WCN-2957)

Figure 2. 30 kW Fuel Cell Powerplant

Scope of Present Program

A feasibility study was conducted to determine the potential of the alkaline fuel cell as the power source in a multi-hundred kilowatt fuel cell electrolysis cell energy storage system. The study identified fuel cell system performance characteristics, a preliminary system conceptual design, system weight and efficiency. As part of the study, alkaline fuel cell technology goals were identified and a preliminary alkaline fuel cell performance prediction was established.

The specific objective of the work planned under Task 1, State-of-the-Art Assessment and Performance Model of Contract No. NAS3-21293 was to conduct a state-of-the-art assessment of alkaline fuel cell technology to define a conceptual design and to identify technology goals for a multi-hundred kilowatt orbital energy storage system for use in a future space vehicle.

Approach

A computer math model was developed to determine component weights for the fuel cell - electrolysis cell energy storage system. The model incorporates the performance characteristics of the fuel cell system, electrolysis cell system and the design guideline weight factors for the solar array, power conditioner, reactant tanks and space radiator.

III. ELECTROCHEMICAL ENERGY STORAGE SYSTEM

This section summarizes the results of a study to define the system weights of a 35 to 25' kW fuel cell-electrolysis cell energy storage system based upon alkaline electrochemical cell technology.

A conceptual design of the energy storage system was established. Employing system design guidelines provided by National Aeronautics and Space Administration, a computer math model which incorporated fuel cell module and electrolysis cell module operating characteristics was developed.

Utilizing the computer model, subsystem weights for the energy storage system were defined. In addition, the impact of fuel cell operating temperature and fuel cell efficiency upon system weight were investigated. In the study the electrolysis cell operates at a temperature of 180°F (82.2°C) and a reactant pressure of 200 psia (138.0 N/cm²).

A. System Concept

The fuel cell - electrolysis cell energy storage concept shown in Figure 3 incorporates a dedicated alkaline fuel cell module and electrolysis cell module. A single power conditioner on the electrical bus for the solar array and electrolysis cell system may be possible. The multi-hundred kilowatt energy storage system is envisioned for application in a future low earth orbit space vehicle.

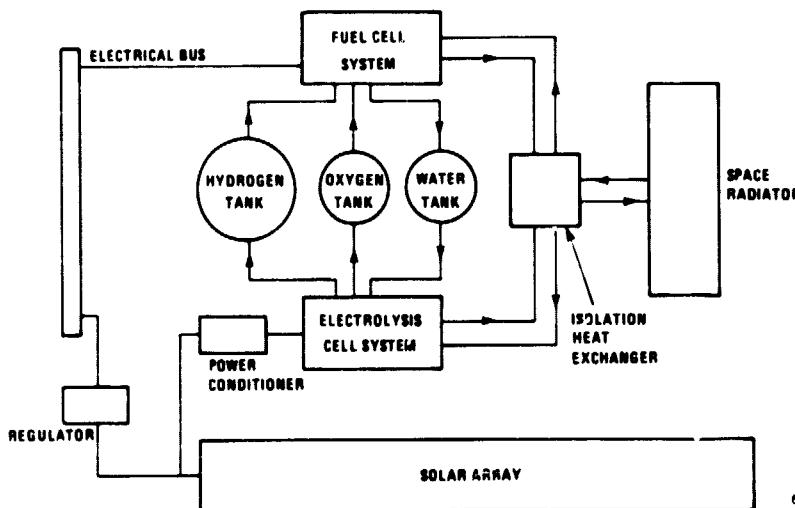


Figure 3.
Fuel Cell Electrolysis Cell
Energy Storage System
Concept

B. System Operation

During the daylight portion of the orbit, the solar array provides power through a voltage regulator to the prime electrical bus system. In addition, the solar array supplies power through a power conditioner to the electrolysis cell module.

The electrolysis cell module generates oxygen and hydrogen for subsequent use in the fuel cell module by the electrochemical decomposition of fuel cell product water. The electrolyzer produced reactants are dried and delivered to reactant storage tanks at a pressure of 200 psia (137.9 N/cm^2). Waste heat from the electrochemical reaction is removed from the electrolysis cell system by a liquid dielectric coolant loop.

In the dark portion of the orbit, the fuel cell module supplies power to the electrical bus by the electrochemical recombination of hydrogen and oxygen. Regulation of the fuel cell module power supplied to the vehicle bus may be unnecessary because of the performance characteristics of the alkaline electrolyte fuel cell. Fuel cell product water is delivered to a 60 psia (41.4 N/cm^2) water storage tank.

A liquid dielectric coolant loop removes waste heat from the fuel cell modules and the electrolysis cell module during operating periods. For standby this loop provides heat to the idle module to maintain operating temperature. In the isolation heat exchanger, waste heat is transferred from the coolant to the space radiator coolant loop. Waste heat from the system radiates to space from this radiator.

C. System Design Guidelines

The system design guidelines shown in Table I were compiled from information provided in Task I, State-of-the-Art Assessment and Performance Model, Statement of Work of Contract No. NAS3-21293 and data sources provided by National Aeronautics and Space Administration - Lewis Research Center. The source of the design criteria for the solar array, reactant tankage, space radiator, and power conditioner was obtained from a study by J. Barry Trout (reference 11).

Parasite power for the fuel cell system was established at 1.26 percent of net power, which is based upon the Power Systems Division developed NAVY fuel cell powerplant which has a parasite power of 378 watts at 30 kW. Parasite power for the electrolysis cell system was established at 1.48 percent of input power, which is based upon Life Systems Inc. estimate of a 250 watt parasite power for a 50-cell electrolyzer unit with a total input power of 18 kW. Parasite power to operate ancillary equipment of the fuel cell electrolysis cell energy storage system in the study by J. Barry Trout (reference 11) was assumed to be 10% of fuel cell system output power.

**TABLE I. FUEL CELL - ELECTROLYSIS CELL ENERGY STORAGE
SYSTEM DESIGN GUIDELINES**

o	System Design Power Levels	
o	Net Power, kW	35, 100, 250
o	Voltage, 120± 10% Vdc	108
o	System Duty Cycles	
o	Dark Period (Fuel Cell) Min.	36
o	Light Period (Electrolysis Cell), Min.	54
o	Continuous (Fuel Cell), hrs.	2
o	Fuel Cell Module	
o	Fuel Cell Performance	Section III.C.1
o	FCM Parasite Power, Percent of Net Power	1.26
o	Electrolysis Cell Module	
o	Electrolysis Cell Performance	Section III.C.2
o	ECM Parasite Power, Percent of Net Power	1.48
o	Power Conditioner	
o	Efficiency, Percent	94
o	Specific Weight, lbs/kW (kg/kW)	5.0 (2.27)
o	Tankage	
o	Minimum Reactant Storage Pressure, psia (N/cm ²)	70 (48.3)
o	Maximum Reactant Storage Pressure, psia (N/cm ²)	200 (137.9)
o	Tank Material	INCONEL
o	Safety Factor	1.5
o	Strength, psi (N/cm ²)	125,000 (86,185)
o	Material Density, lbs/in ³ kg/m ³	0.3 (8303)
o	Space Radiator	
o	Emissivity	0.92
o	Thermal View Factor, Light Period	0.5
o	Thermal View Factor, Dark Period	1.0
o	Sink Temperature, °F (°C)	-127 (-88)
o	Radiator Specific Weight, lbs/ft ² (kg/m ²)	1.13 (5.53)
o	Solar Array	
o	Specific Weight, lbs/kW (kg/kW)	45.15 (20.5)

1. Fuel Cell Performance

The fuel cell performance employed in this study is shown on Figure 4. The performance is based upon Power System Division's standard production cell configuration used in the Space Shuttle Orbiter power plant. This cell configuration consists of a gold-platinum catalyst cathode, a reconstituted asbestos matrix, a platinum-palladium catalyst anode, and a porous nickel electrolyte reservoir plate unitized into a fiberglass-epoxy cell edge frame.

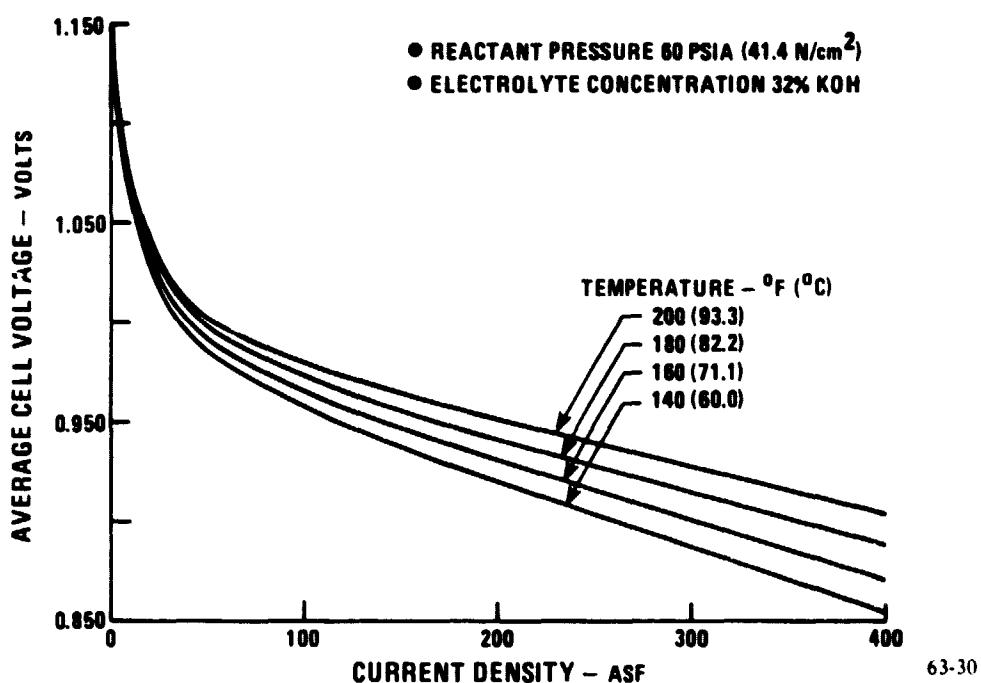


Figure 4. Alkaline Fuel Cell Performance

The endurance capability of the fuel cell is limited by the allowable voltage loss. This is shown graphically on Figure 5. This figure shows fuel cell performance as a function of operating time, with the top curve as initial performance and each successive decrease in performance level representing an increase in operating time.

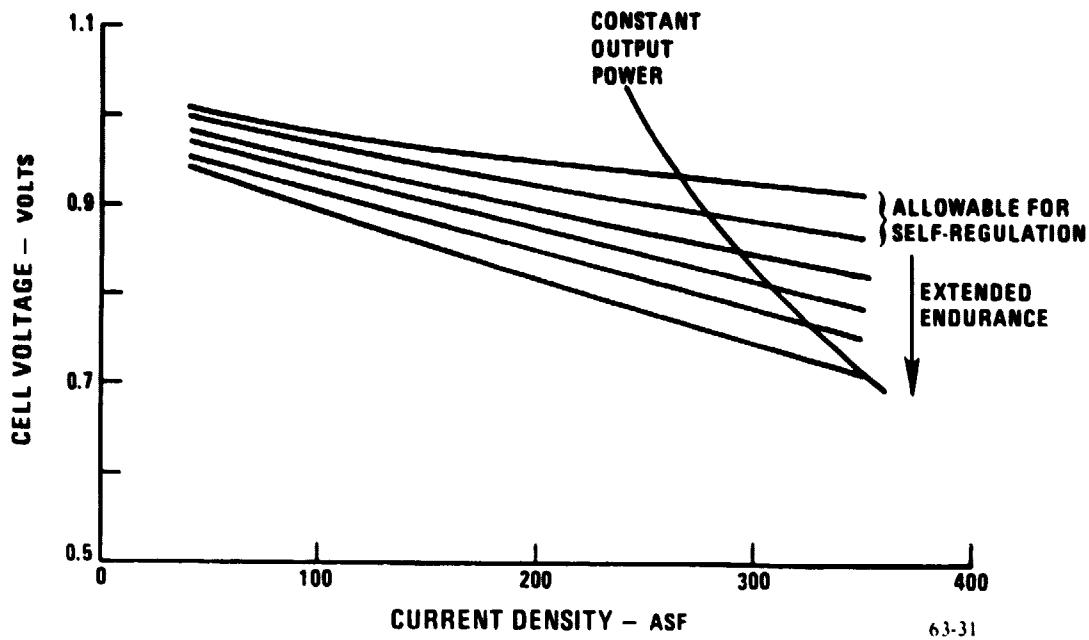


Figure 5. Fuel Cell Endurance Capability

The Orbiter Fuel Cell Powerplant, for example, has an allowed performance reduction for self-voltage regulation. Allowing a greater voltage reduction translates into extended endurance capability.

The predicted performance of an alkaline fuel cell configuration featuring the stable platinum-on-carbon catalyst anode configuration currently being evaluated under the Lewis program is presented in Section IV. A multi-cell stack featuring supported catalyst anode cells completed a 5,000-hour endurance test at 100 ASF (107.6 ma/cm^2) with no loss in cell performance at 100 ASF (107.6 ma/cm^2) and during 2-hour performance calibrations at 400 ASF, conducted at 1000-hour intervals during the test. A summary of the 5,000-hour endurance test is presented in reference 1.

2. Electrolysis Cell Performance

The electrolysis cell performance employed in this study is presented in Figure 6. The performance is based upon test experience of alkaline electrolyte water electrolyzers currently under development by Life Systems Inc., Cleveland, Ohio.

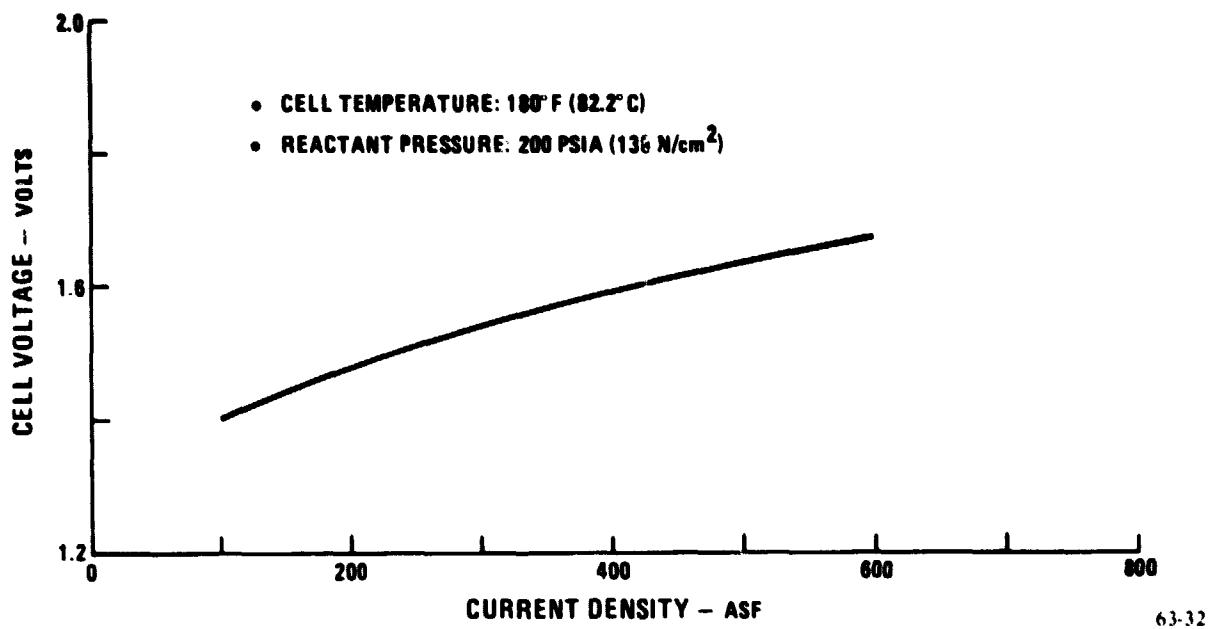


Figure 6. Alkaline Electrolysis Cell Performance

D. System Weight

A system weight breakdown for a 100 kW fuel cell electrolysis cell energy storage system for a baseline and an advanced technology fuel cell system has been established. The system weight breakdown is presented in Table II.

TABLE II. 100 KW ENERGY STORAGE SYSTEM WEIGHT BREAKDOWN
lbs (kg)

	Baseline	Advanced Technology
o Solar Array	10,475 (4751)	10,274 (4660)
o Space Radiator	982 (445)	645 (293)
o Tanks and Reactants	1,309 (594)	257 (117)
o Water Tank	21 (10)	0.4 (.2)
o Hydrogen Tank	749 (340)	65 (30)
o Oxygen Tank	374 (170)	33 (15)
o Reactants	165 (74)	159 (72)
o Isolation Heat Exchanger	48 (22)	42 (19)
o Fuel Cell System	1,331 (604)	1,042 (473)
o Electrolysis Cell System	934 (424)	888 (403)
o Power Conditioner	653 (296)	631 (285)
o Total Weight - lbs (kg)	15,732 (7136)	13,779 (6,250)
o Fuel Cell Operating Temp - °F (°C)	140 (60)	200 (93.3)
o Fuel Cell Operating Current Density - ASF (ma/cm ²)	308 (332)	308 (332)
o Electrolysis Cell Operating Temperature - °F (°C)	180 (82.2)	180 (82.2)
o Electrolysis Cell Current Density - ASF (ma/cm ²)	317 (341)	325 (350)

The high performance of the alkaline fuel cell results in a total system weight of 15,732 lbs (7,136 kg) at the baseline fuel cell module 140°F (60°C) operating temperature. For comparison with batteries, the energy storage portion of the system, that is, the fuel cell module, electrolysis cell module, reactants and tanks has an energy storage density of 55.8 watt-hours/lb (123 watt-hours/kg). This value includes the two-hour continuous fuel cell module operation requirement.

Increasing the fuel cell system operating temperature from 140°F (60°C) to 200°F (93.3°C) as shown in Figure 7 reduces the baseline energy storage system weight by 691 lbs (313.4 kg) which is only a four-percent weight savings. The major contributer to energy storage system weight is the solar array. The solar array accounts for approximately 66 percent of the total system weight.

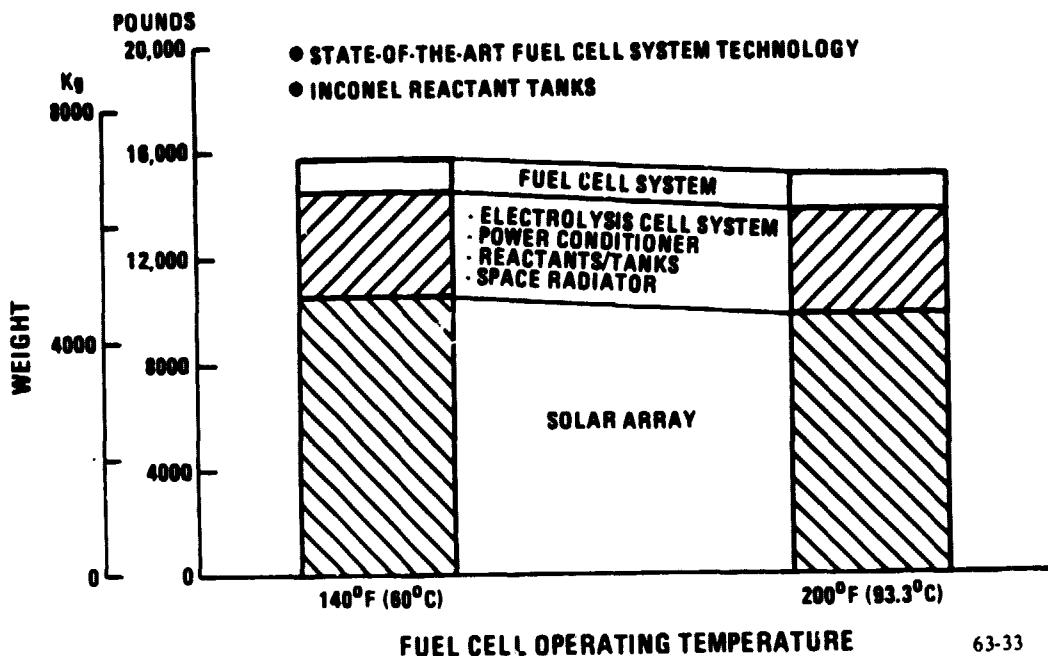


Figure 7. 100 kW Energy Storage System Weight Comparison

The slightly higher total system weight of the low temperature baseline system would be offset by the demonstrated long-life capability of low temperature alkaline electrolyte fuel cells. Two lightweight single cells (reference 2) featuring supported catalyst anodes completed 8,085 cell-hours of endurance operation with little change in performance.

A reduction in baseline system weight can be accomplished by replacing the standard porous nickel electrolyte reservoir plate (ERP) in the fuel cell module with the lightweight graphite ERP currently being evaluated under the Lewis Research Center program. Further weight savings result with the use of lightweight, high-strength filament-wound reactant tanks, replacing the heavy Inconel tanks in the baseline system. Incorporating the lightweight graphite ERP into the PSD developed 30 kW Navy fuel cell powerplant results in a 19 percent reduction in fuel cell system weight as shown in Table III.

**TABLE III. FUEL CELL SYSTEM WEIGHT COMPARISON
NAVY 120-CELL FUEL CELL POWERPLANT
30 kW**

	Baseline	Advanced Technology
o Power Section	221.5	165.8
o Accessory Section	68.2	68.2
Total Weight - lbs	289.7	234.0

The advanced technology energy storage system weight shown in Table II incorporates these two lightweight system features, that is lightweight graphite ERP's and filament-wound reactant tanks, which results in a 1953 lb (886 kg) or a 12.4 percent weight savings. The energy storage density of the energy storage portion of the advanced technology system is 91.4 watt-hours/lb (201.6 watt-hours/kg) at the 100 kW power level.

The fuel cell module in the baseline energy storage system consists of six stacks of 120, 0.508 ft² (471.9 cm²) active area cells connected electrically in parallel. At the design point of 100 kW, the fuel cell module operates at an average cell temperature of 140°F (60°C) and a reactant pressure of 60 psia (41.4 N/cm²) at a current density of 308 ASF (331.5 mA/cm²) with a cell voltage of 0.898 V. The electrolysis cell module consists of four stacks of 67, 1.0 ft² (929 cm²) active area cells connected electrically in parallel. The electrolysis cell module operates at an average cell temperature of 180°F (82.2°C) and a reactant pressure of 200 psia (137.9 N/cm²) at a current density of 317 ASF (341 mA/cm²) with a cell voltage of 1.607 V. The overall efficiency for the baseline system is 50.4 percent.

1. Computer Model

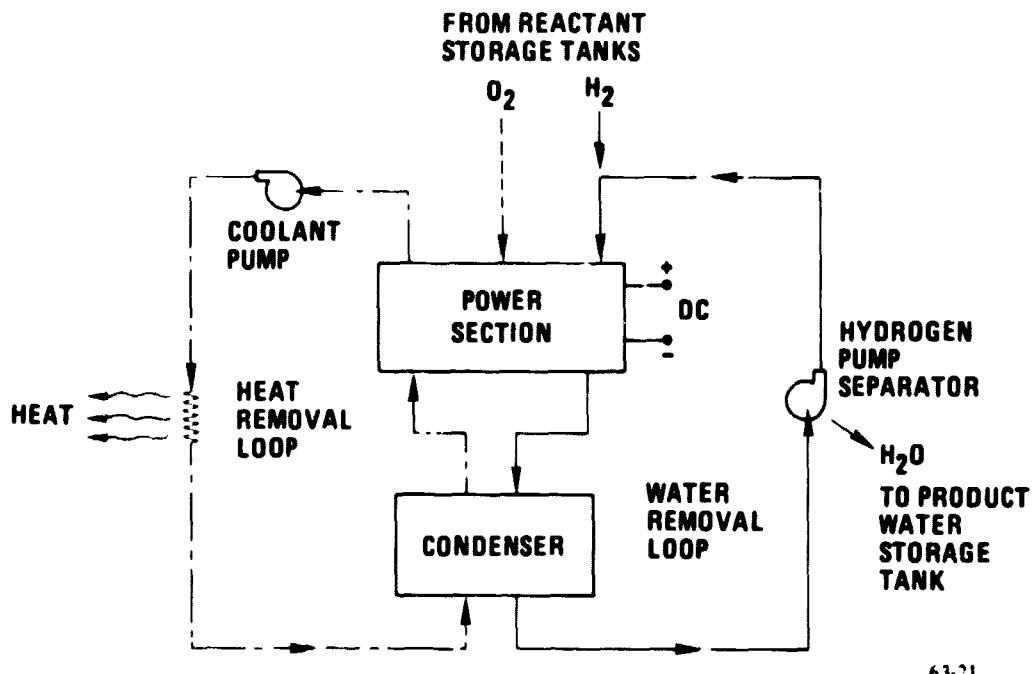
A computer math model was developed to determine component weights for the energy storage system. The model incorporates the performance characteristics of

the fuel cell module, electrolysis cell module and the design guideline weight factors for the solar array, power conditioner, reactant tanks and space radiator.

The operating requirements for the fuel cell module and electrolysis cell module are established in the model from the system duty cycle and system bus power. At the design power level, the model internally identifies the minimum energy storage system weight.

a. Fuel Cell System

The fluid schematic of the fuel cell system is shown in Figure 8. This schematic also describes the operation of the Navy and Space Shuttle Orbiter fuel cell powerplants developed by Power Systems Division.



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Figure 8. Fuel Cell System Fluid Schematic

Reactants are supplied to the power section from the storage tanks by a demand-type pressure regulator. These valves assure that the reactant pressure within the power section is maintained at 60 psia (41.4 N/cm^2) over the full range of reactant flows.

Product water is removed by the dynamic water removal method. Product water evaporates into the circulating hydrogen stream and is vented from the power section. The water enriched hydrogen stream passes through a condenser, the product water is condensed, separates from the hydrogen stream and is subsequently stored in the product water tank.

Waste heat is removed from the power section by circulating a liquid dielectric coolant through the condenser and through cooler assemblies within the power section. The fuel cell waste heat is rejected through an isolation heat exchanger to the space radiator coolant system.

The fuel cell module weight relationship developed for the computer model includes the weight for a complete system, that is, power section, pumps, controls, instrumentation, insulation, and structure.

The baseline fuel cell powerplant incorporates a fuel cell assembly and accessory section identical to those developed for the Space Shuttle Orbiter and Navy powerplants. The advanced technology fuel cell powerplant incorporates the lightweight graphite electrolyte reservoir plate being evaluated under the Lewis Research Center program (reference 1). In order to further reduce weight, the power section of the advanced technology fuel cell powerplant has four cells dedicated to each cooler assembly compared to the two cells per cooler in the Space Shuttle Orbiter powerplant.

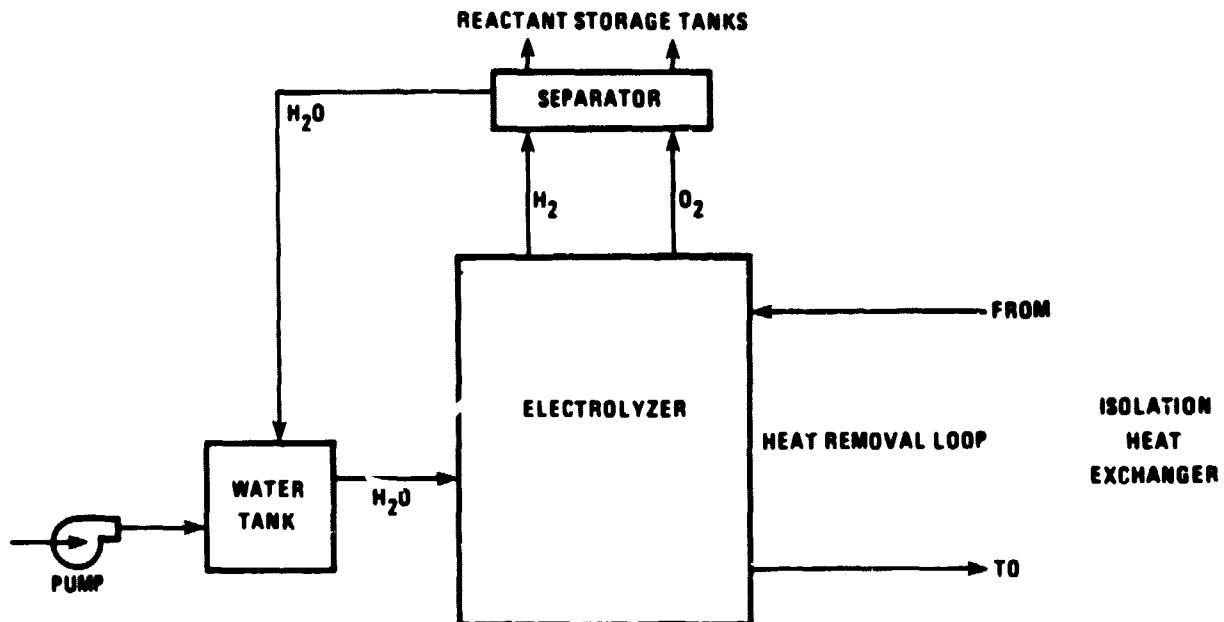
The fuel cell system weight relationship developed for the computer model is based upon the 0.508 ft^2 (471.9 cm^2) active area cell configuration employed in the NASA and Navy fuel cell powerplants. For the model, fuel cell system weight is a function of net power and the total number of cells within the power section.

Electrolysis cell system weight is based upon a 1.0 ft² (929 cm²) active area cell. In the model, like the fuel cell system, the electrolysis cell system weight is a function of input power and total number of cells within the electrolyzer.

Parasite power for the fuel cell system was established at 1.26 percent of net power, which is based upon the Power System Division developed Navy fuel cell powerplant which has a parasite power of 378 watts at 30 kW.

b. Electrolysis Cell System

The fluid schematic of the electrolysis cell system is shown in Figure 9.



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Figure 9. Electrolysis Cell System Fluid Schematic

The electrolysis cell system employs the Static Feed Water Electrolyzer concept developed by Life Systems, Inc., Cleveland, Ohio. The electrolysis cell system obtains fuel cell product water from the energy storage system water storage tank and electrolyzes it into hydrogen and oxygen. The electrolyzer in the system

operates at a pressure of 200 psia (137.9 N/cm²). A water pump in the electrolysis cell system periodically refills the electrolysis cell module water tank, pressurizing the water to 200 psia (137.9 N/cm²).

A mockup of a 60-cell electrolyzer employing state-of-the-art Life System Inc. cell technology is shown in Figure 10.

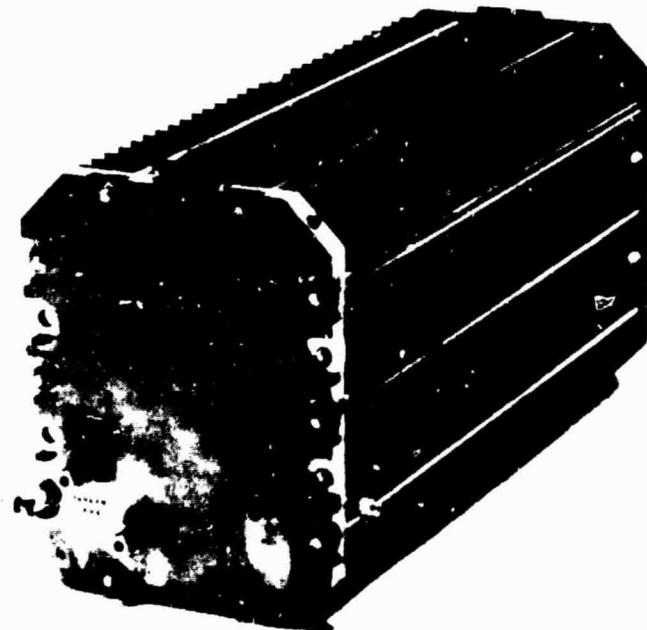


Figure 10.
Life System Inc 60-Cell Electrolyzer

(W-5065)

The electrolysis cell system includes a separator between the electrolyzer and the reactant storage tanks to remove water vapor in the electrolyzer produced hydrogen and oxygen. This water vapor must be removed from the reactants prior to storage or the water will collect in the reactant storage tanks. The amount of water vapor in the reactants is controlled by the electrolyzer operating conditions, temperature, pressure, and concentration. The water from the separator is returned to the electrolysis cell module water tank.

The electrolysis cell module water tank is a small tank which is periodically filled from the energy storage system fuel cell system product water tank. A pump takes the fuel cell product water from 60 psia (41.4 N/cm²) to 200 psia (137.9 N/cm²) in filling the storage tank.

The heat removal loop maintains the electrolyzer at the design operating temperature of 180°F (82.2°C). During the dark portion of the orbit when the electrolysis cell system is at standby, high temperature coolant from the fuel cell system is circulated through the electrolyzer to maintain operating temperature. During the light portion of the orbit when the electrolysis cell system is operating, circulating coolant removes waste heat from the electrolyzer, transferring this heat through the isolation heat exchanger to the space radiator.

The electrolysis cell system weight relationship developed for the fuel cell electrolysis cell energy storage system computer model includes the weight for a complete system, that is, electrolyzer, pumps, controls, instrumentation, insulation and structure. The weight breakdown of a 50-cell electrolyzer supplied to Mr. J. K. Stedman of Power System Division by Mr. F. Schubert of Life System Inc., employed in developing the electrolysis weight relationship, is shown in Table IV.

TABLE IV. WATER VAPOR FEED ELECTROLYSIS UNIT WEIGHT
50-CELL ELECTROLYZER
18 kW

o Electrolyzer	186 lbs
o Accessory Section	61 lbs
Total Weight	247 lbs

The weight of the electrolyzer is based upon 1.0 ft² (929 cm²) active area electrolysis cells. The 61 lbs (27.7 kg) of accessory section weight includes the weights for a reactant pressure regulator, water feed tank, structure, plumbing, valves, and controls.

Parasite power for the electrolysis cell system was established at 1.48 percent of input power, which is based upon Life System Inc. estimate of a 250 watt parasite power for the 50-cell electrolyzer unit with a total input power of 18 kW.

c. Reactant Storage Tanks

Oxygen, hydrogen, and water tank weights are determined internally in the computer program from input values for maximum storage pressure, material strength, design safety factor, and material density. Reactant tank weights are for spherical tanks with storage volume sufficient for two-hours of continuous fuel cell module operation. A summary of reactant tank design guidelines is presented in Table V.

TABLE V. REACTANT TANK DESIGN GUIDELINES

o Material	Inconel
o Safety Factor	1.5
o Min. Tank Temperature	70°F (21.1°C)
o Min. Storage Pressure	70 psia (48.3 N/cm ²)
o Max. Storage Pressure	200 psia (137.9 N/cm ²)

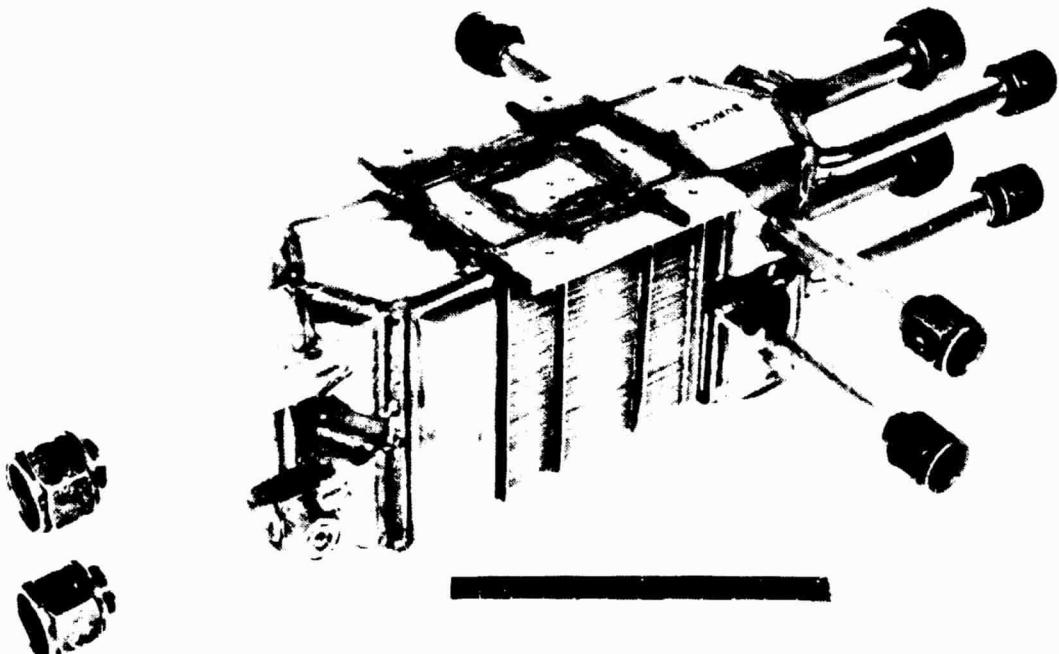
The capability to input tank material properties, material strength and density allows the investigation of the effect of lightweight, high-strength filament-wound reactant tanks on total system weight. As shown in Table VI the strength of the filament-wound tanks is approximately 2.3 times that of Inconel with one-sixth the density.

TABLE VI. REACTANT TANK MATERIAL PROPERTY COMPARISON

	Baseline	Advanced Technology
o Material	Inconel	Filament-Wound
o Strength - psi (N/cm ²)	125,000 (86,185)	286,000 (197,191)
o Density - lbs/in ³ (kg/m ³)	0.3 (8303)	0.049 (1356)

d. Isolation Heat Exchanger

The isolation heat exchanger weight is derived from the lightweight Space Shuttle Orbiter fuel cell powerplant interface heat exchanger shown in Figure 11.



(WO-1239)

Figure 11. Space Shuttle Orbiter Interface Heat Exchanger

The Space Shuttle Orbiter interface heat exchanger weighs 16.4 lbs (7.4 kg) with a specific weight of 1.20 lbs/kW (.5 kg/kW)

e. Space Radiator

The Stephan-Boltzman relationship was used to define the surface area of the space radiator required to dissipate system waste heat. From the surface area, given a radiator specific weight, the weight of the space radiator can be defined. A summary of the space radiator design guidelines is presented in Table VII.

TABLE VII. SPACE RADIATOR DESIGN GUIDELINES

o Thermal Emissivity	0.92
o Thermal View Factor - Light Period	0.5
o Thermal View Factor - Dark Period	1.0
o Sink Temperature	-127°F (-88.3°C)
o Radiator Specific Weight - lbs/Ft ² (kg/m ²)	1.13 (5.53)

Space radiator weight was established from the subsystem waste heat, fuel cell module or electrolysis cell module, with the appropriate thermal view factor (reference 11) which resulted in the largest radiator area and therefore weight. A thermal view factor of 1.0 was used during fuel cell operation (dark period) and a thermal view factor of 0.5 was used during electrolysis cell operation (light period).

f. Solar Array

The weight of the solar array required in the energy storage system was determined by applying a specific weight of 45.15 lbs/kW (20.5 kg/kW) to required solar array output power. Solar array output power was defined as the sum of the light period vehicle power requirement, total electrolysis cell module input power, and fuel cell module parasite power.

g. Power Conditioner

In the fuel cell electrolysis cell energy storage system, a power conditioner on the input power to the electrolysis cell system may be required. An electrical efficiency of 94 percent for the device was utilized. To define the weight of the power conditioner a specific weight of 5.0 lbs/kW (2.27 kg/kW) was employed.

2. Weight Trade-off Studies

Weight trade-off studies were conducted to investigate the impact of fuel cell module operating temperature, fuel cell and electrolysis cell efficiency, and system output power on total system weight.

Two types of fuel cell systems were evaluated, (1) a baseline system and (2) an advanced technology system. The baseline fuel cell system is based upon the Power Systems Division developed fuel cell powerplants that have been delivered to the National Aeronautics and Space Administration and the Navy. The advanced technology fuel cell system features a power section with lightweight graphite electrolyte reservoir plates currently being evaluated under the Lewis Research Center Program. In addition the advanced technology energy storage systems employs high-strength, lightweight filament-wound reactant tanks.

a. Fuel Cell Operating Temperature

The impact of fuel cell operating temperature upon the weight of a 100 kW energy storage system was investigated. Fuel cell module operating temperatures between 140°F (60°C) and 200°F (93.3°C) with baseline and advanced technology fuel cell configurations were studied. Computer calculated storage system weights as a function of fuel cell operating temperature are shown in Figure 12.

As shown in Figure 12 increasing the state-of-the-art fuel cell operating temperature from 140°F (60°C) to 200°F (93.3°C), reduces total system weight by 691 lbs (313 kg) which is only a 4 percent weight saving. The slightly higher total system weight of the 140°F (60°F) state-of-the-art system would be offset by the demonstrated long-life capability of low-temperature alkaline electrolyte fuel cells. Two lightweight single cells (reference 2) featuring the new supported catalyst anodes completed 8,085 cell-hours of endurance operation with little change in performance.

The high performance of the alkaline electrolyte fuel cell results in a total system weight of 15,732 lbs (7,136 kg) at the design point for the 100 kW baseline energy storage system.

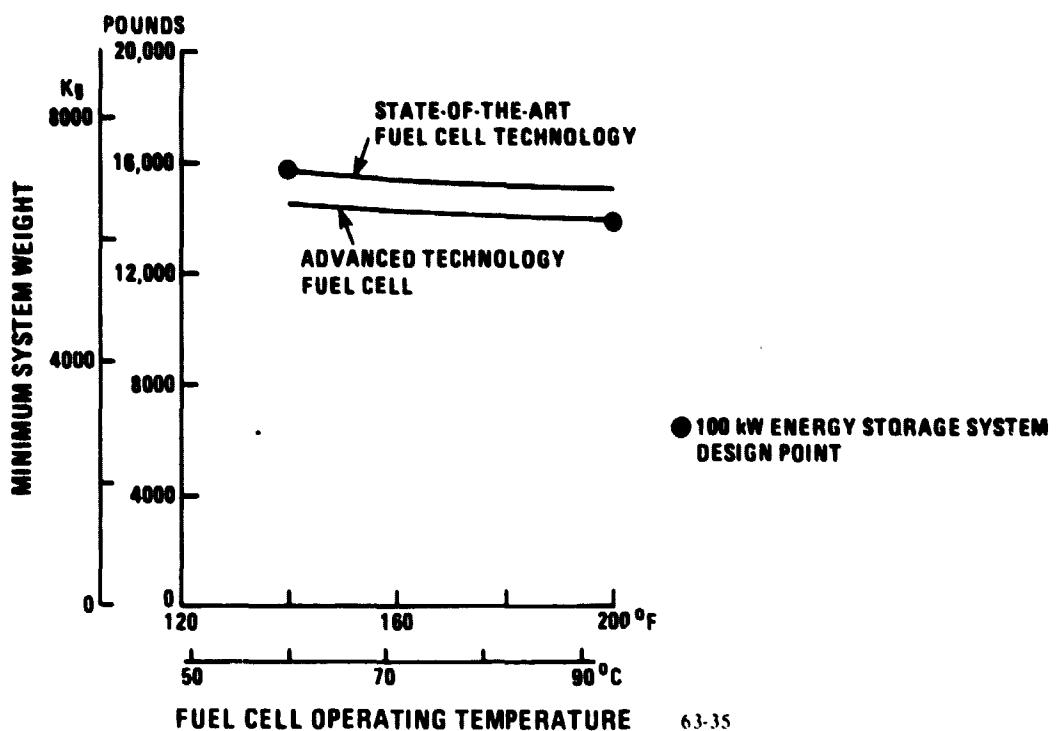


Figure 12. Impact of Fuel Cell Operating Temperature on System Weight

A reduction in energy storage system weight can be accomplished by replacing the standard porous nickel electrolyte reservoir plate (ERP) in the fuel cell system with the lightweight graphite ERP's being evaluated under the Lewis Research Center program (reference 1). Further system weight savings are obtained with the use of lightweight, high-strength, filament-wound reactant tanks, replacing the heavy Inconel tanks employed in the baseline system. Incorporating these two lightweight components into the 100 kw energy storage system result in a total system weight of 13,779 lbs (6,250 kg) at the design point, which represents a 12.4 percent weight savings over the state-of-the-art system.

A system weight breakdown for the baseline and advanced technology fuel cell system is presented in Table II.

A description of the fuel cell module and electrolysis cell module employed in the baseline 100 kw energy storage systems is summarized in Table VIII.

TABLE VIII. 100 kW ENERGY STORAGE SYSTEM DESCRIPTION BASELINE

o Fuel Cell System	
o Number of Stacks	6
o Number of Cells/Stack	120
o Current Density - ASF (ma/cm ²)	308 (332)
o Cell Voltage - volts	.898
o Efficiency - percent	71.5
o Weight - lbs	1331 (604)
o Electrolysis Cell System	
o Number of Stacks	4
o Number of Cells/Stack	67
o Current Density - ASF (ma/cm ²)	317 (341)
o Cell Voltage - volts	1.607
o Efficiency - percent	78.1
o Weight - lbs (kg)	934 (424)
o Energy Storage System Efficiency -percent	50.4

Fuel cell system efficiency for the study was defined as the total fuel cell system output power divided by the total energy input to the system. The normal practice in fuel cell systems is to define total input energy as the lower heating value of hydrogen ($LHVH_2$) in Btu's per pound times the system hydrogen consumption rate. Combining terms, fuel cell efficiency becomes:

$$\text{Efficiency (fuel cell)} = \frac{41,182 \text{ (Cell Voltage -volts)}}{LHVH_2} \times 100$$

Electrolysis cell system efficiency was defined as the total energy output from the system divided by the power input from the power conditioner. Output energy is the $LHVH_2$ times the system hydrogen production rate. Combining terms, electrolysis cell efficiency becomes

$$\text{Efficiency (electrolysis cell)} = \frac{LHVH_2}{41,182 \text{ (Cell Voltage-volts)}} \times 100$$

For comparison with nickel-cadmium and nickel-hydrogen batteries, electrochemical efficiency is defined for the fuel cell as cell voltage divided by the theoretical cell potential and for the electrolysis cell as the theoretical cell potential divided by electrolysis cell voltage. The electrochemical efficiency of the fuel cell and electrolysis cell described in Table VIII is 73.3 percent and 76.5 percent, respectively.

The overall energy storage system efficiency was defined as the watt-hours provided to the electrical bus by the fuel cell system divided by the watt-hours into the electrolysis cell system from the solar array. This translates into the following definition.

$$\text{Efficiency (overall)} = .667 \frac{\text{Net Fuel Cell System Output (kW)}}{\text{Total Electrolysis Cell System Input (kW)}} \times 100$$

The constant 0.667 is equal to the dark period operating time (fuel cell) divided by the light period operating time (electrolysis cell) or 36 minutes divided by 54 minutes. The system duty cycles for the fuel cell and electrolysis cell are presented in Table 1, Section III.C.

b. Fuel Cell Efficiency

The impact of fuel cell current density upon system weight was investigated. To improve fuel cell efficiency, an increase in design cell voltage is necessary, which results in lower current density operation. However as fuel cell efficiency is increased, additional fuel cell stacks are required to meet output power requirements. The increased number of stacks increases fuel cell system weight. Figure 13 shows the effect of fuel cell efficiency upon energy storage system weight at a 140°F (60°C) fuel cell operating temperature for a 100 kW energy storage system.

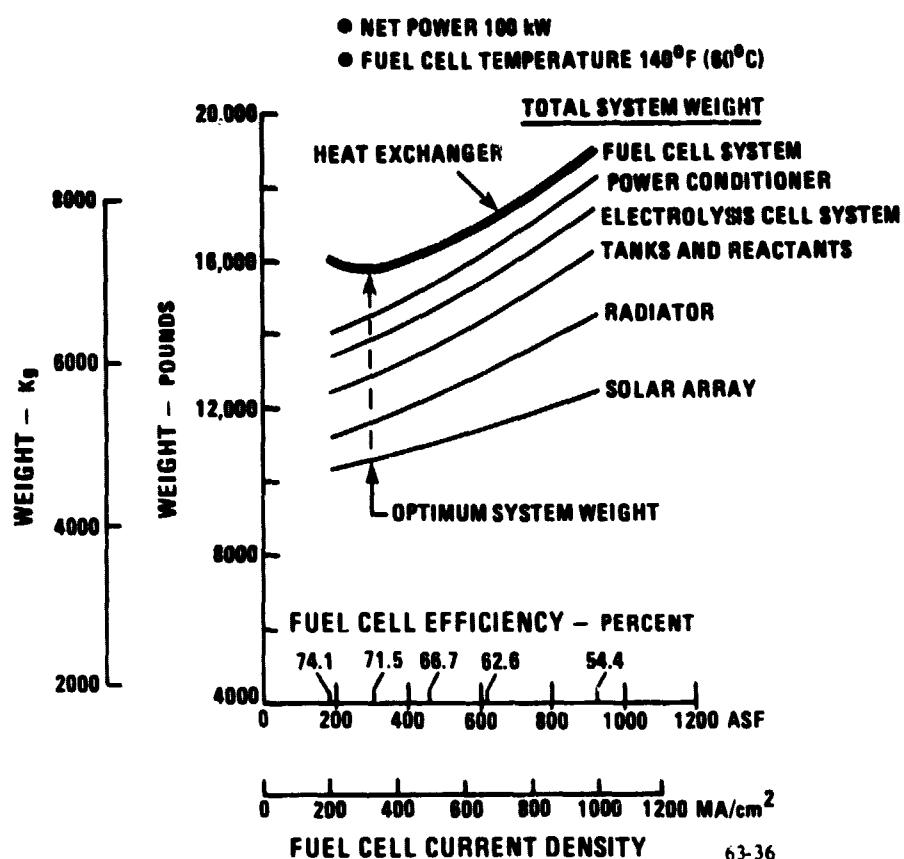


Figure 13. Effect of Fuel Cell Current Density Upon System Weight

The minimum baseline 100 kW energy storage system weight of 15,732 lbs (7,135.9 kg) occurs at a fuel cell efficiency of 71.5 percent for an overall system efficiency of 50.4 percent. The majority of the total system weight is accountable to the solar array, 10,475 lbs (4,751.4 kg) or 66.6 percent of the system weight.

The weight of the individual subsystems, solar array, space radiator, tanks and reactants, electrolysis cell module, isolation heat exchanger, and power conditioner decrease as the fuel cell module becomes more efficient. However as fuel cell system efficiency increases, fuel cell current density decreases requiring additional fuel cell stacks, a greater number of cells and a heavier system. Figure 14 shows the impact of fuel cell efficiency on fuel cell module weight.

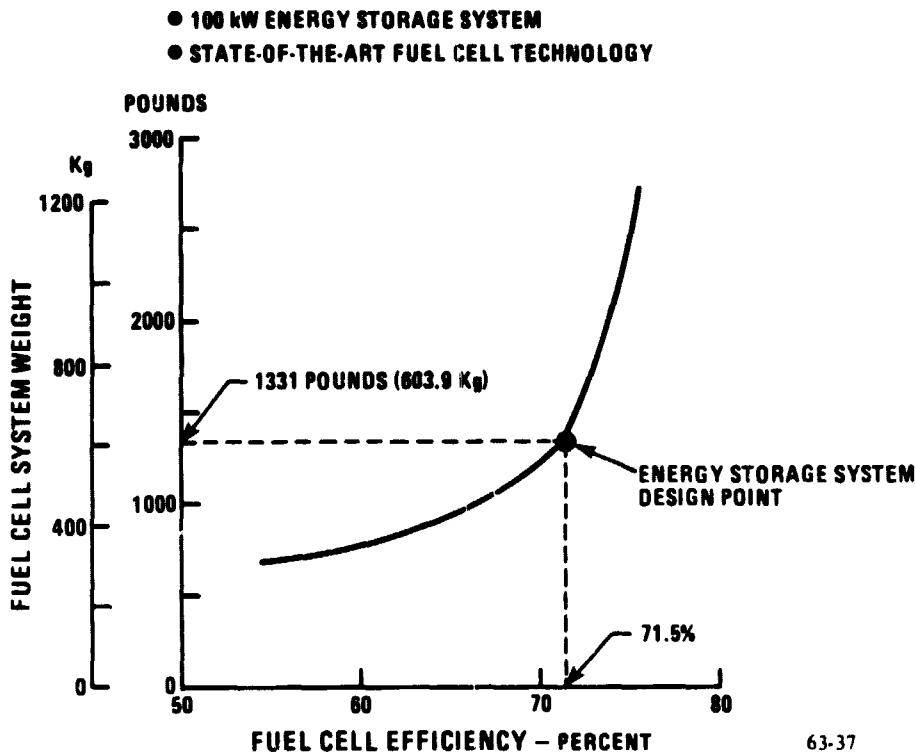


Figure 14. Effect of Fuel Cell Efficiency on Fuel Cell Module Weight

Table IX summarizes the fuel cell system configurations employed in generating the information shown in Figure 14.

TABLE IX. FUEL CELL SYSTEM WEIGHT COMPARISON

o Fuel Cell Module				
o Number of Stacks	2	4	6	8
o Number of Cells/Stack	158	129	120	118
o Current Density - ASF (ma/cm ²)	923 (994)	461 (496)	308 (332)	231 (249)
o Cell Voltage - Volts	.684	.837	.898	.914
o Fuel Cell Efficiency - %	54.5	66.7	71.5	72.8
o Fuel Cell System Weight lb (kg)	682 (309)	1002 (454)	1331 (604)	1689 (766)
o Electrolysis Cell Weight-lbs (kg)	1179 (535)	997 (452)	934 (424)	913 (414)
o Reactant/Tank Weight-lbs (kg)	1719 (780)	1404 (637)	1309 (594)	1286 (583)
o Radiator Weight-lbs (kg)	2077 (942)	1222 (554)	982 (445)	924 (419)
o Isolation HX Weight-lbs (kg)	101 (46)	60 (26)	48 (22)	45 (20)
o Power Conditioner Weight-lbs (kg)	859 (390)	700 (318)	653 (296)	642 (291)
o Solar Array Weight-lbs (kg)	12336 (5595)	10899 (4944)	10475 (4751)	10377 (4707)
o Total System Weight-lbs (kg)	18953 (8597)	16284 (7386)	15732 (7136)	15877 (7202)
o System Efficiency	38.7	47.5	50.4	51.7

The weight of the energy storage system does not appear to be a strong function of electrolysis cell efficiency. The effect of electrolysis cell efficiency upon total system weight is shown in Figure 15. A variation in electrolysis cell efficiency of six percent above and below the system design point at an electrolysis cell efficiency of 78 percent, results in a total system weight variation of 347 lbs (157 kg) or only 2 percent.

Table X summarizes the electrolysis cell system configuration employed in generating the information shown in Figure 15.

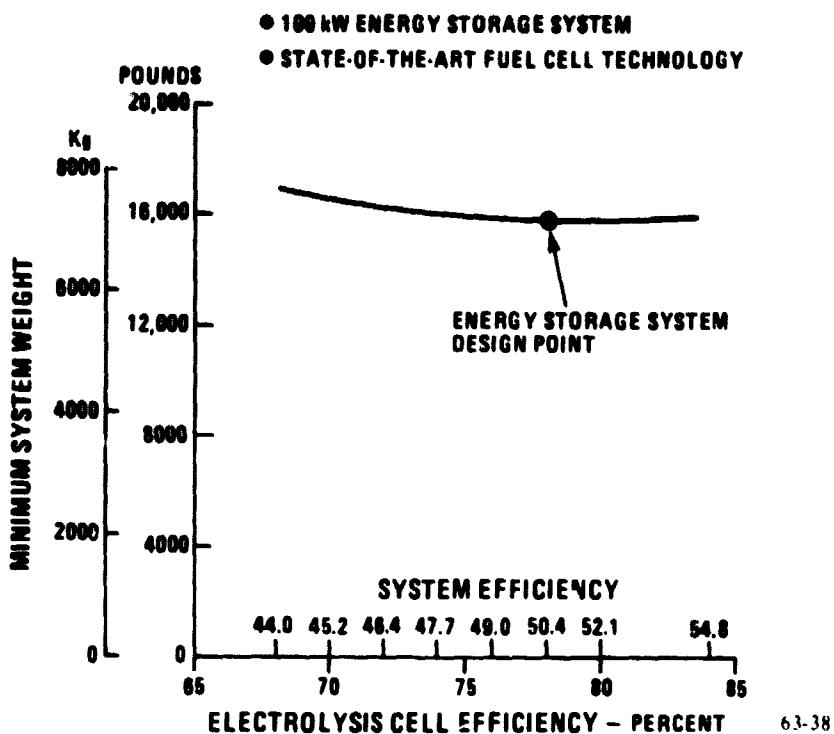


Figure 15. Effect of Electrolysis Cell Efficiency on System Weight

TABLE X. ELECTROLYSIS CELL SYSTEM WEIGHT COMPARISON

Electrolysis Cell Module			
o Number of Stacks	2	4	6
o Number of Cells/Stack	64	69	72
o Current Density-ASF (mA/cm^2)	526 (566)	257 (277)	169 (182)
o Cell Voltage - volts	1.697	1.570	1.495
o Electrolysis Cell Efficiency	.74	.80	.84
o Electrolysis Cell Weight-lbs (kg)	660 (299)	1098 (498)	1555 (705)
o Fuel Cell System Weight-lbs (kg)	1350 (612)	1464 (664)	1474 (669)
o Reactant/Tank Weight-lbs (kg)	1306 (592)	1292 (586)	1291 (586)
o Radiator Weight-lbs (kg)	1182 (536)	978 (444)	975 (442)
o Isolation HX Weight-lbs (kg)	50 (23)	48 (22)	48 (22)
o Power Conditioner Weight-lbs (kg)	696 (316)	637 (289)	606 (275)
o Solar Array Weight-lbs (kg)	10865 (4928)	10330 (4686)	10051 (4559)
o Total System Weight-lbs (kg)	16109 (7307)	15847 (7188)	16000 (7257)
o System Efficiency	47.7	54.1	54.8

c. System Output Power

The system weights for a 35 kW and 250 kW fuel cell-electrolysis cell energy storage system were determined. The weights presented in Figure 16 for a 140°F (60°C) and 200°F (93.3°C) fuel cell operating temperature are based upon a baseline fuel cell module.

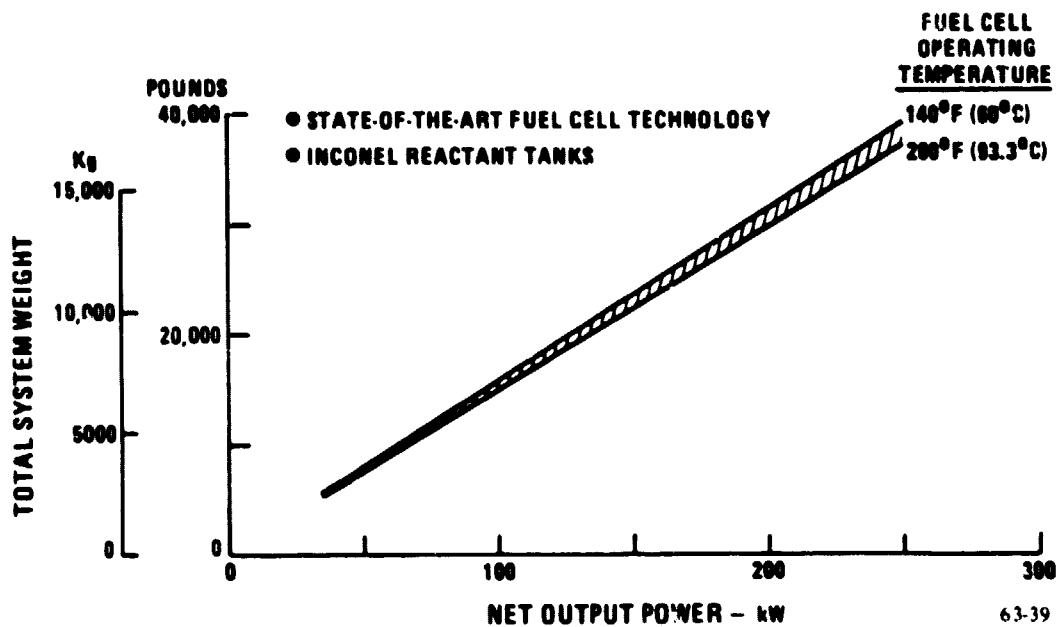


Figure 16. Impact of Output Power on System Weight

The higher fuel cell operating temperature of 200°F (93.3°C) compared to the baseline 140°F (60°C) operating temperature results in a total system weight reduction for a 35 kW system of only 271 lbs (122.9 kg) or 5.1 percent and for a 250 kW system of only 1771 lbs (803.3 kg) or 4.7 percent. A subsystem weight breakdown for the 35 kW and 250 kW energy storage system at a 140°F (60°C) fuel cell operating temperature is presented in Table XI. A similar weight breakdown for the 100 kW system is presented in section III.C.

A description of the fuel cell system and electrolysis cell system employed in the 35 kW and 250 kW energy storage system is summarized in Table XII.

**TABLE XI. 35 kW and 250 kW ENERGY STORAGE SYSTEM WEIGHT BREAKDOWN
BASELINE, 140°F (60°C)**

	35 kW	250 kW
o Solar Array -lbs (Kg)	3,676 (1667)	26,304 (11,931)
o Radiator -lbs (Kg)	364 (165)	2,441 (1,107)
o Tanks and Reactants -lbs (Kg)	456 (207)	3,217 (1,459)
o Water Tank	2 (1)	12 (5)
o Hydrogen Tank	264 (120)	1863 (845)
o Oxygen Tank	132 (60)	931 (422)
o Reactants	58 (26)	411 (187)
o Isolation Heat Exchanger -lbs (Kg)	17 (8)	118 (54)
o Fuel Cell System -lbs (Kg)	481 (128)	3,386 (154)
o Electrolysis Cell System -lbs (Kg)	379 (172)	1,970 (894)
o Power Conditioner -lbs (Kg)	230 (104)	1,646 (747)
o Total Weight - lbs (Kg)	5,603 (2541)	39,082 (17,727)

**TABLE XII 35 kW and 250 kW ENERGY STORAGE SYSTEM DESCRIPTION
BASELINE, 140°F (60°C)**

	35 kW	250 kW
o Fuel Cell System		
o Number of Stacks	2	16
o Number of Cells Per Stack	121	120
o Current Density - ASF (ma/cm ²)	323 (348)	288 (306)
o Cell Voltage - volts	.891	.902
o Efficiency - percent	71.0	71.9
o Weight - lbs (kg)	481 (218)	3386 (1536)
o Electrolysis Cell System		
o Number of Stacks	1	8
o Number of Cells Per Stack	67	66
o Current Density - ASF (ma/cm ²)	310 (330)	358 (381)
o Cell Voltage - volts	1.503	1.629
o Efficiency - percent	78.0	77.1
o Weight - lbs (kg)	379 (172)	1970 (894)

d. Technology Improvement Areas

A substantial reduction in fuel cell weight and improvement in operating life is expected with the introduction into the alkaline electrolyte fuel cell the lightweight and stable cell components developed under the Lewis Research Center Program.

The lightweight graphite electrolyte reservoir plate configuration being evaluated under the Lewis Research Center program reduces the weight of a 0.508 ft² active area cell from 175 gms to 145 gms which represent a 47 percent reduction in cell weight. Graphite electrolyte reservoir plates have been incorporated into the Second Advanced Technology Four-Cell Stack Rig which has completed over 3,500 hours of testing with little reduction in cell performance.

The new polysulfone fiberglass laminate cell edge frame structure has shown to be very stable during corrosion testing. Based upon corrosion test results, incorporating the new frame structure into the 0.508 ft² (472 cm²) active area cell design could contribute to a 30-percent improvement in long-term performance. A carbonate analysis of the cells from the First Advanced Technology Four-Cell Stack revealed that the advanced technology cells fabricated with hybrid polysulfone edge frames had a 44 percent lower electrolyte carbonate level than the production fiberglass-cell epoxy edge frame cell.

Increased temperature capability, therefore, increased performance, and improved performance stability has been demonstrated with an asbestos-reinforced potassium titanate matrix. Endurance testing of a laboratory research cell incorporating an asbestos reinforced potassium titanate matrix has completed 5,250 hours of testing of a cell temperature of 200°F (93.3°C) and 200 ASF (215.3 mA/cm²) with no loss in cell performance. This matrix configuration has been incorporated into the Second Advanced Technology Four-Cell Stack and the Cyclical Load Profile Six-Cell Stack endurance tested (reference 1) under the Lewis Research Center Program.

e. Weight into Orbit

A preliminary estimate of the weight into orbit over a 30-year operating period for the baseline energy storage system was made. The weight into orbit represents the initial system weight plus the weight of system components which would be replaced during the operating life of the system.

The assumed operating life and replacement interval of the pumps, valves and controls, fuel cell modules, and electrolysis cell modules is presented in the following discussion.

The operating life of the pumps in the system was assumed to be 10,000 hours or 1.1 years. A hydrogen circulation pump tested by United Technologies successfully completed 10,000 hours of testing during the Shuttle Prototype Powerplant Demonstration Program.

Valves and controls within the system were assumed to have a capability of 60,000 cycles or 5.2 years of operation at the energy storage system design guideline duty cycle presented in Section III.C. The 60,000 cycle life estimate was established from discussions with the technical specialists at United Technologies who are familiar with valve and control characteristics.

The operating life of the fuel cell modules at the 140°F (60°C) operating temperature was estimated to be 27,000 hours or 3.1 years. Extrapolating the endurance capability of full-size cells which operated in the region of 165°F (73.9°C) to 200°F (93.3°C) by the reciprocal of temperature, a standard corrosion rate parameter, established the fuel cell operating capability of 27,000 hours at the 140°F (60°C) temperature.

The operating life of the electrolysis cell modules at the 180°F (82.2°C) was assumed to be 35,000 hours or 4 years. An electrolysis cell endurance tested by Life Systems, Inc. (LSI) completed 20,000 hours (reference 12) of testing at a

temperature of 180°F (82.2°C) with little change in performance. A 75 percent increase, equivalent to 15,000 hours of additional life beyond the 20,000 hour test data was assumed in this preliminary study.

The estimated weight into orbit, defined as initial system weight plus component replacement weight, for the baseline energy storage system as a function of power and vehicle operational life is shown in Figure 17. The baseline system incorporates baseline fuel cell modules and electrolysis cell modules. The fuel cell modules are constructed with standard production cells which are employed in the Space Shuttle Orbiter fuel cell powerplant and the fuel cell powerplants delivered to the U.S. Navy. The electrolysis cell modules incorporate Life Systems, Inc. (LSI) water electrolysis cells with an active area of 1.0 ft² (929 cm²).

Incorporating the technology advances into the fuel cell modules resulting from the Lewis Research Center sponsored programs with United Technologies which is discussed in Section III.D.2.e. would result in a substantial reduction in system weight and improvement in operating life.

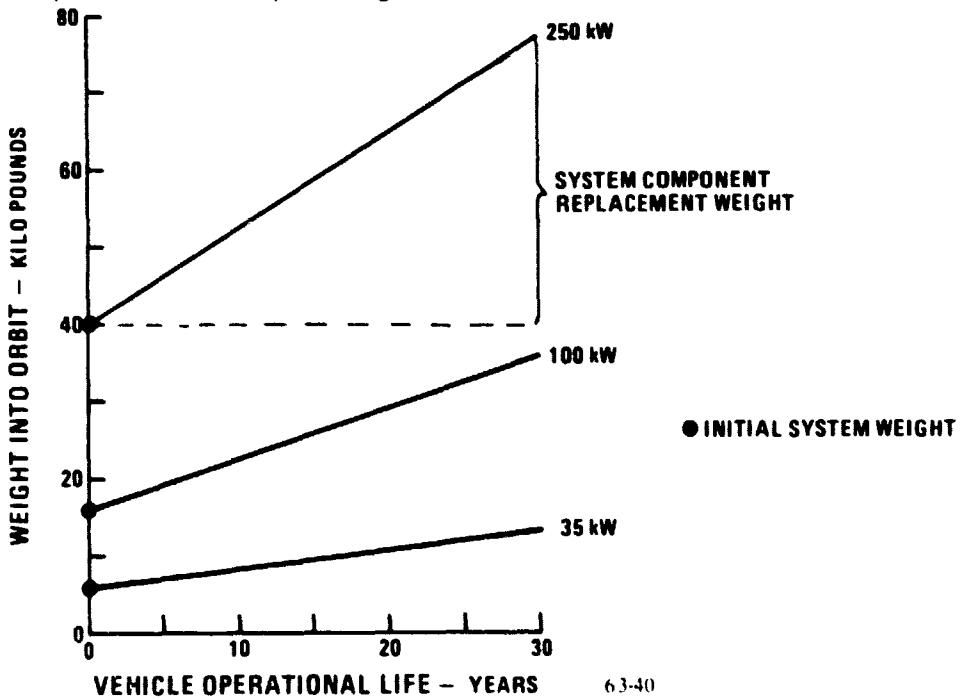


Figure 17. Weight to Orbit, Baseline Energy Storage System

E. Fuel Cell System Cost

Power Systems Division (PSD) cannot estimate the cost of the fuel cell module without a definite program and schedule because the level of concurrent activity at PSD on alkaline fuel cells has a very strong impact on the cost to assembly, test, and delivery of the system.

IV. FUEL CELL PERFORMANCE PREDICTION

A performance prediction for the alkaline fuel cell incorporating the advanced technology platinum-on-carbon catalyst anode configuration was defined. Endurance tests sponsored by the National Aeronautics and Space Administration - Lewis Research Center of alkaline electrolyte fuel cells incorporating the new supported catalyst anode configuration have exhibited high, stable performance with no long-term loss in performance.

The performance of the alkaline fuel cell with a platinum-on-carbon catalyst anode is shown in Figure 18.

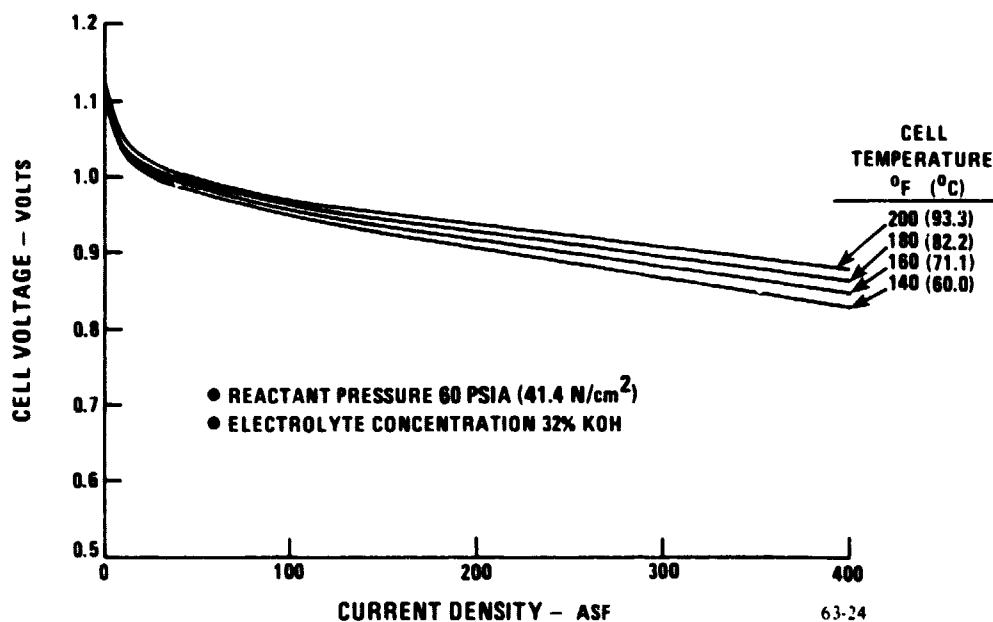


Figure 18. Alkaline Fuel Cell Performance Prediction

The performance levels shown are based upon the NASA-Lewis Advanced Technology Four-Cell Stack Rig 39461-1 which successfully completed a scheduled 5000-hour endurance test at a nominal 180°F (82.2°C) cell temperature with no loss in cell performance. These performance levels incorporate all the activation, polarization and internal resistance losses which characterize actual fuel cell performance.

Based upon available long-term endurance test data, the performance of the new platinum-on-carbon catalyst anode cell configuration after 5000 hours of operation would remain unchanged at the levels shown in Figure 1. The supported catalyst anode cells in the advanced technology four-cell stack rig 39461-1 completed 5000 hours of operation at 100 ASF (107.6 ma/cm²) with no loss in performance at 100 ASF (107.6 ma/cm) and during 2-hour performance calibrations at 400 ASF (430.6 ma/cm²) conducted at 1000-hour intervals during the test.

APPENDIX

Alkaline Electrolyte Fuel Cell Development Background

United Technologies has demonstrated reduction to practice for the alkaline technology by the Apollo fuel cell powerplant, Navy underwater fuel cell powerplants, and the fuel cell powerplants for the Space Shuttle Orbiter.

All of these delivery powerplants, Apollo, Space Shuttle and Navy, met firm specification requirements and operated successfully in spacecraft and submersibles.

Apollo

In 1959 United Technologies ran a full-scale power section with Bacon-type cells. The test installation is shown in Figure 19.

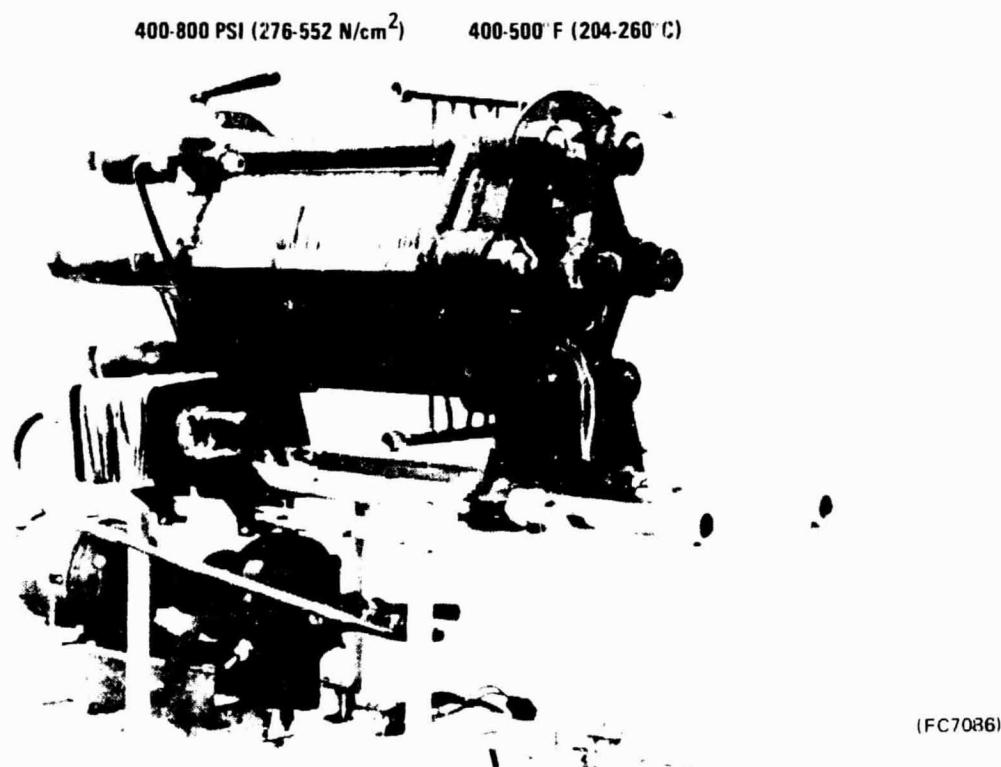


Figure 19. Bacon Fuel Cell Stack (1959)

In 1962 the first PC-3A fuel cell powerplants in flight configuration were delivered under the Apollo program. The Apollo fuel cell powerplant was qualified for manned space flight in 1965 and 92 production powerplants were delivered by 1969.

The Apollo fuel cell powerplant is shown in Figure 20. The nominal rating was 1.5 kW at 28 volts with an overload capability of 2.3 kW. The powerplant weighed 241 lbs (109 kg) and was furnished with shock mounts within the cylindrical support skirt. Three PC-3A powerplants installed in the Command and Service Module provided the primary source of electrical power for the Apollo missions.

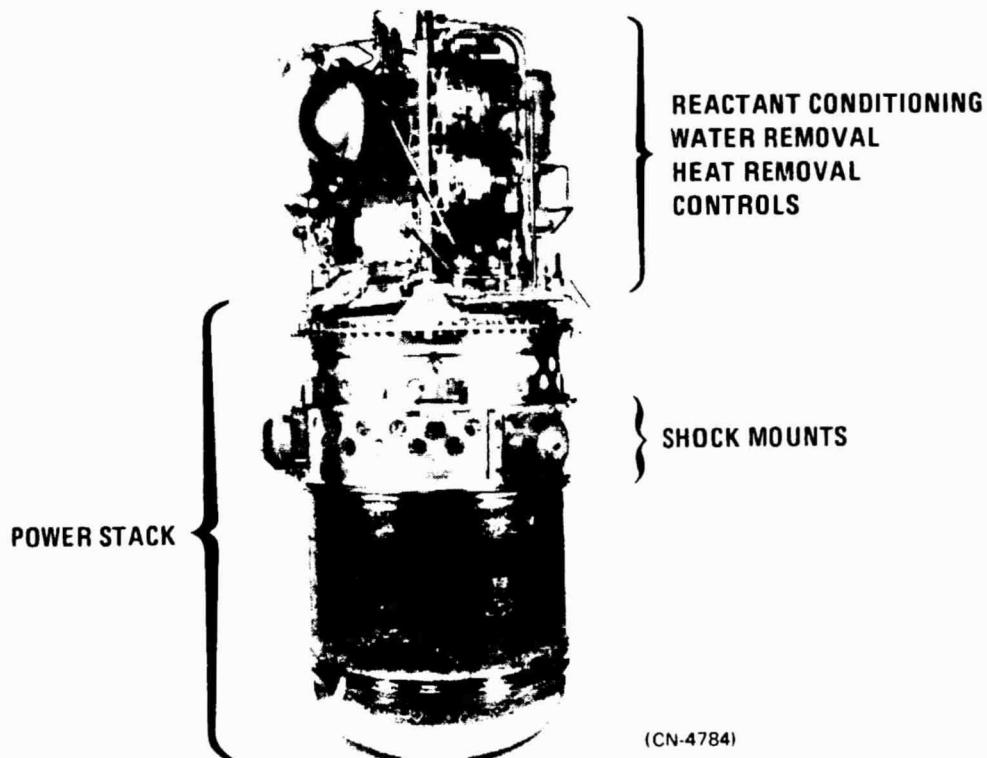
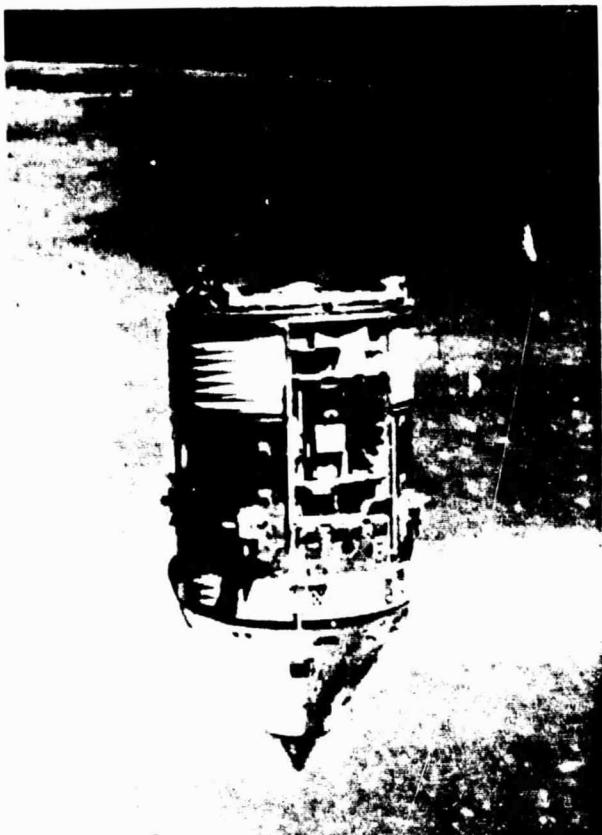


Figure 20. Apollo Fuel Cell Powerplant

The flight experience with the Apollo powerplant is summarized in Figure 21. More than 10,000 hrs of flight time were logged on 54 powerplants during 18 missions during the Apollo, Apollo-Soyuz, and Spacelab programs.

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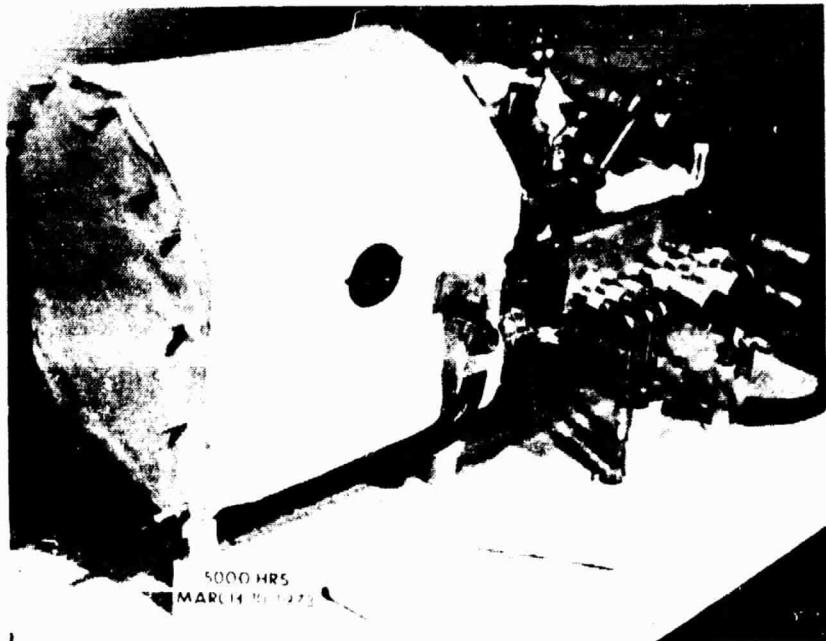
- PRIME POWER FOR COMMAND AND SERVICE MODULES
- 18 FLIGHTS INCLUDING:
 - 9 LUNAR/3 SKYLAB
 - 1 APOLLO SOYUZ
- 10,750 HOURS OF FLIGHT TIME
- 90 POWERPLANTS DELIVERED

(WCN-1283)

Figure 21. Apollo Fuel Cell Powerplant

Space Shuttle Orbiter Powerplants

The technology for the Space Shuttle fuel cell powerplants was established by the DM-2 powerplant which was developed and demonstrated under a Technology Demonstrator program conducted for the Johnson Space Center. Figure 22 summarizes the results of a 5,000-hr test of the DM-2 powerplant at United Technologies facility. This test includes 31 simulated missions. The powerplant was shut down, cooled down, and restarted for each mission and operated to a variable load profile. The Demonstration started on August 8, 1972 and was completed in eight months on March 10, 1973. No maintenance was conducted on the powerplant during this demonstration. The powerplant was refurbished with a new power section and new bearings in the hydrogen pump and delivered to Johnson Space Center where another 5,000-hour test was completed without maintenance.



- 5072 HOUR TEST TO ORBITER LOAD PROFILE
- NASA-REQUIRED WATER QUALITY FOR ENTIRE TEST
- 21 SELF-ENERGIZED STARTS

(FC7092)

Figure 22. Shuttle Prototype Powerplant Endurance Test

In addition during the DM-2 powerplant program two, six-cell power sections were endurance tested, accumulating 10,000 and 10,500 hours of operation as shown on Figure 23, and a hydrogen circulation pump was tested for 10,000 hours.

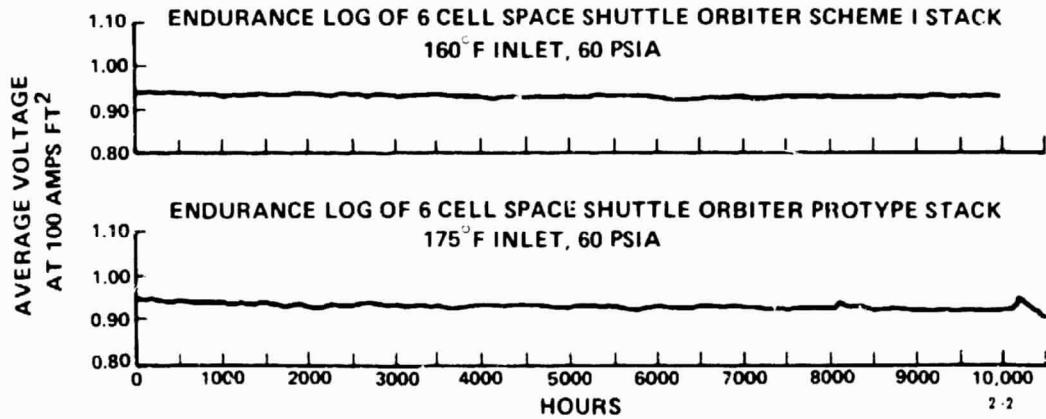
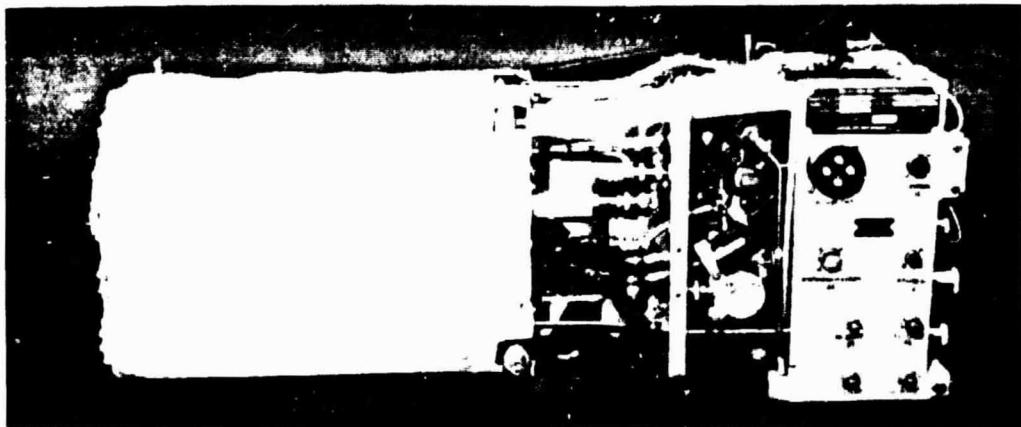


Figure 23. 10,000 Hour Power Section Tests

Three PC17 fuel cell powerplants provide the only source of electrical power on board the Space Shuttle Orbiter.

Figure 24 shows the Orbiter powerplant. The Orbiter powerplant has a nominal maximum power rating of 12 kW with an emergency overload rating of 16 kW. The Orbiter powerplant is smaller than the Apollo powerplant and weights 40 lbs (18 kg) less and delivers eight times the power. The Orbiter powerplant does not require shock or vibration isolation and is hard mounted to the vehicle structure.



(WCN-6742)

Figure 24. Orbiter Fuel Cell Powerplant

The Orbiter fuel cell program started in January 1974. The first development powerplant test started in October 1975. Three development powerplants accumulated 8770 hours of test including accelerated vibration and operation in a simulated space vacuum.

The Orbiter fuel cell powerplant was qualified for manned space flight in June 1979. A 2000-hour qualification test including ten mission cycles and 60 start/stop cycles was completed in January 1980.

Figure 25 is a summary of production powerplants. The three powerplants for the Orbiter Space Craft OV099 were originally delivered in November 1976 for use in the Orbiter Space Craft Enterprise during the Approach and Landing Test Program. These powerplants were refurbished with minor modifications and delivered in October 1980 and have demonstrated five years of shelf life.

- **8 powerplants delivered**
 - OV 101 FCP's (3)
 - OV 101 spare
 - Qualification FCP
 - OV 102 FCP's (3)
- **4 powerplants refurbished**
 - OV 102 spare
 - OV 099 FCP's (3)
- **5 powerplants on order**
 - OV 103 FCP's (3)
 - OV 104 FCP's (2)
- **1 refurbishment scheduled**
 - OV 104 FCP

FC10030
PG 10004

Figure 25. Production Summary

Service experience with the Orbiter fuel cell powerplant is summarized in Figure 26. A total of 1269 hours have been accumulated on six powerplants installed in the Orbiter Space Crafts "Enterprise" and "Columbia". The service experience includes eight flights during the Approach and Landing Tests from May to October 1977 and the first Orbital flight of STS-1 in April 1981.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

- 1260 HOURS ON 6 POWER PLANTS
- "ENTERPRISE"
 - APPROACH AND LANDING TESTS
 - MAY 1977 TO OCTOBER 1977
 - 8 FLIGHTS
 - 636 HOURS
 - 12 STARTS
 - "COLUMBIA"
 - INTEGRATED SYSTEMS TEST – JANUARY 1980
 - FLIGHT READINESS FIRING – FEBRUARY 1981
 - FIRST ORBITAL FLIGHT (STS-1) – APRIL 1981
 - 633 HOURS
 - 3 STARTS

(WCN-598G)

Figure 26. Service History

Navy Powerplants

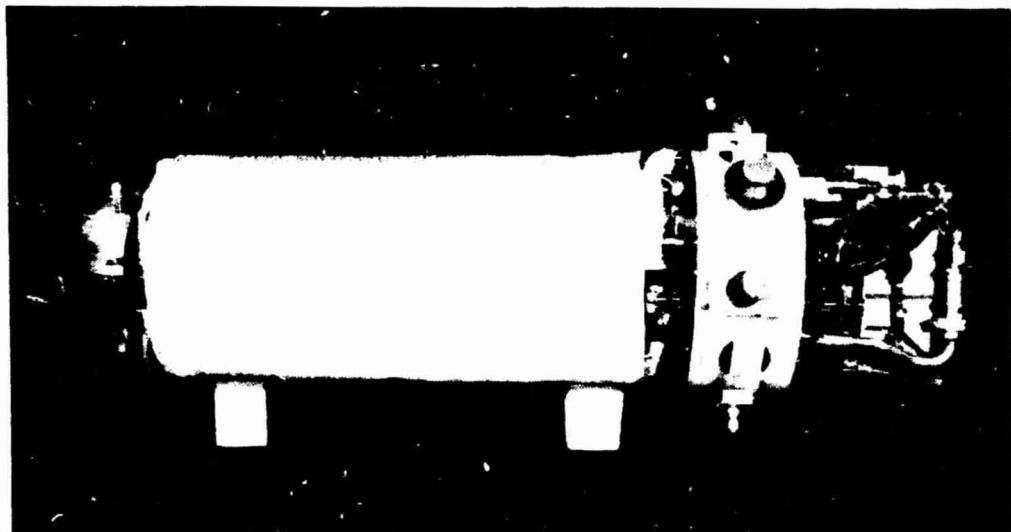
In 1968 the National Academy of Science recommended that the Navy develop hydrogen/oxygen fuel cells for use in energy systems with extended endurance capability in the 1 to 100 kW range.

Studies for the Deep Submergence Search Vehicle conducted for the Deep Submergence Systems Project Office of the Navy established the requirement for a Fuel Cell Power System.

In November 1970, the Navy established a contract with UTC for the design, development, and delivery of a 20 kW 120 volt powerplant. The powerplant was delivered in May 1971 and met all specification requirements.

In 1973 the Navy ordered a 700 kWhr, 60 kW power system for use in submersibles like the Deep Submergence Rescue Vehicle. This system included two 30 kW 120 volt powerplants installed in containment vessels for service at a depth of 5000 feet, a control unit and storage vessels for hydrogen, oxygen and product water.

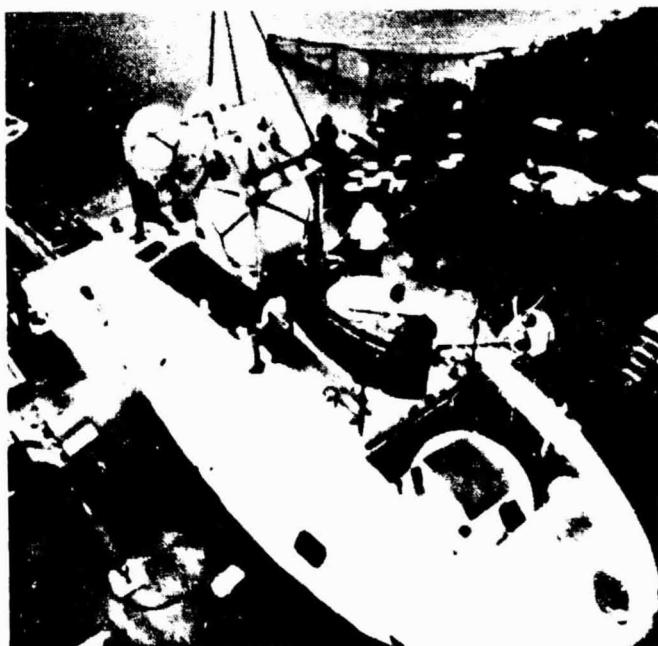
Figure 27 shows the Navy powerplant and its characteristics. More than 7000 hours of operation were accumulated in development testing and field operation.



- POWER SOURCE FOR DEEP SUBMERGENCE RESCUE VEHICLE (DSRV)
- TEN POWERPLANTS BUILT
- MORE THAN 7000 HOURS OF OPERATION
- WEIGHT - 391 LBS
- VOLUME - 5.5 FT³
- ENVELOPE - 14" DIA x 72" LONG

Figure 27. 30-kW Fuel Cell Powerplant

Figure 28 shows the installation of the power system in Deep Quest and a summary of operations. A total of 360 hours of operation was completed during 28 missions in Deep Quest during two periods of operation: August 1979 through January 1980 and April 1980 through September 1980.



- 360 HOURS
- 22 DIVES IN 10 MONTHS
 - SEPTEMBER 1979 TO JANUARY 1980
 - APRIL 1980 TO SEPTEMBER 1980
- VERIFIED OPERATION AT 5000 FT DESIGN DEPTH
- 46 HOURS ENDURANCE RECORD FOR SUBMERSIBLES
 - 550 kWhr WITH NO PURGING

(WCN-5419)

Figure 28. Operation Submersible "Deep Quest"

In-House Demonstrator Powerplants

The PC8B series of powerplants was developed under in-house sponsored programs to improve upon the Apollo powerplant in the areas of performance, startup characteristics, operating characteristics, endurance and powerplant weight. The PC8B powerplants are shown in Figure 29.

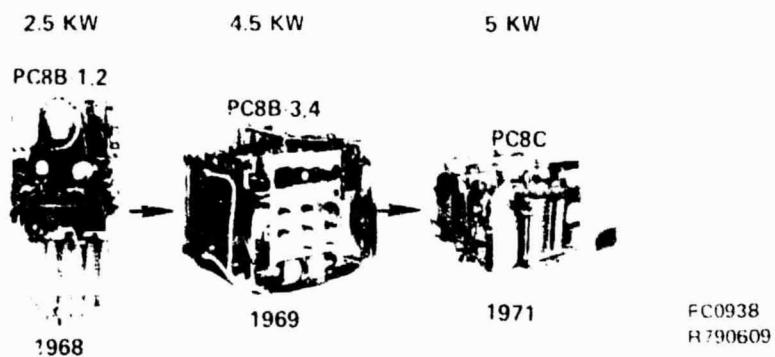


Figure 29. PC8B Demonstrator Powerplants

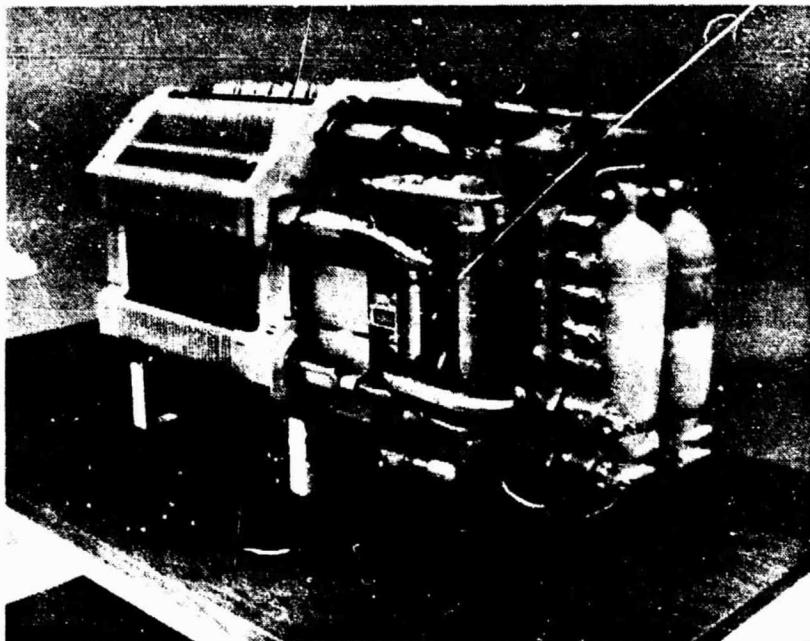
The PC8B-1 was the first powerplant incorporating low-temperature, matrix-type alkaline cells configured for a space application. Cell active area of 0.4 ft² (371.6 cm²) was the same as Apollo. The PC8B-1 retained the Apollo ancillaries and mounting structure. The PC8B-2 was identical to the PC8B-1 except the interface panel and mounting structure were modified for compatibility with the Air Force Manned Orbiting Laboratory.

In 1969, the PC8B was repackaged with a stack of 0.508 ft² (471.9 cm²) active area cells. Designated the PC8B-3, this powerplant was operated as an in-house demonstration unit for more than a year, accumulating 97 starts and more than 6000 hours of reactants. With an improved cooling system, its power rating was raised from 2.5 kW to 5 kW and it was designated the PC8B-4.

The 5 kW PC8C was built in 1971 with a stack of 0.508 ft² (471.9 cm²) active area cells of the high power density type. This cell configuration was developed in the late 1960's in Air Force and internal research and development programs. Originally developed for operation at very high current densities, typically 3000 ASF (3229 mA/cm²), the cell was found to have superior endurance as well. Endurance testing of this cell configuration in a National Aeronautics and Space Administration Lewis Research Center Program demonstrated over 11,000 hours of operation and a subscale laboratory cell in an internal research and development program exceeded 35,000 hours of testing. This cell configuration has been employed in all subsequent low-temperature alkaline fuel cell powerplants. The PC8C was used as an in-house demonstrator powerplant for nearly two years. During this period it accumulated 100 self-energized starts.

The X712 in-house demonstrator powerplant, Figure 30, was similar to the DM-2 powerplant but incorporated a power section of 36, 0.508 ft² (471.9 cm²) active area cells with a higher performing gold-platinum cathode catalyst replacing the platinum cathode catalyst employed on the DM-2 cell.

X712 has a greater capacity coolant system than the DM-2, giving it a continuous output rating of 15 kW. X712 has been employed as a demonstrator powerplant for four years accumulating 115 self-energized starts.



(WCN-2036)

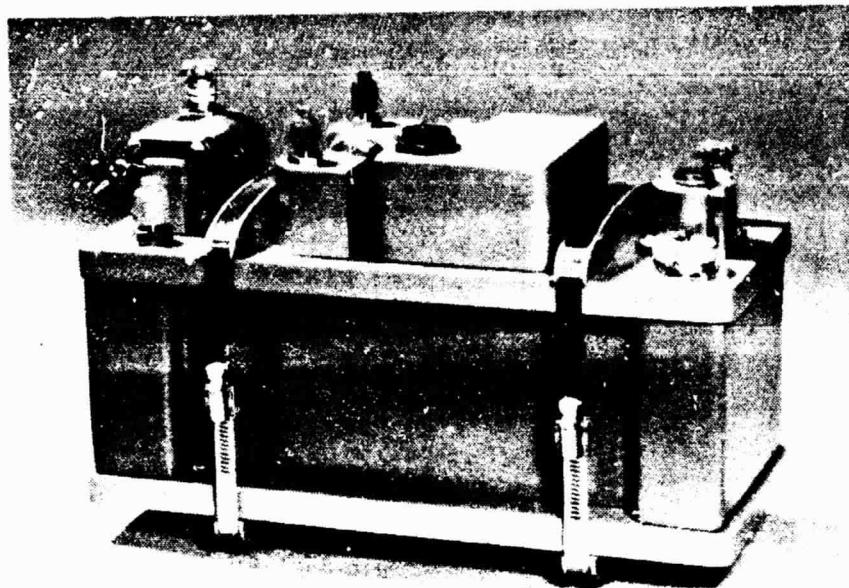
Figure 30. X712 Demonstrator Powerplant

Lightweight Fuel Cell Powerplant

A lightweight 3.5 kW fuel cell powerplant shown in Figure 31 was developed under a program sponsored by NASA-George C. Marshall Space Flight Center. The design is based upon the advanced technology lightweight fuel cell which operates with passive water removal developed under the Lewis Research Center program.

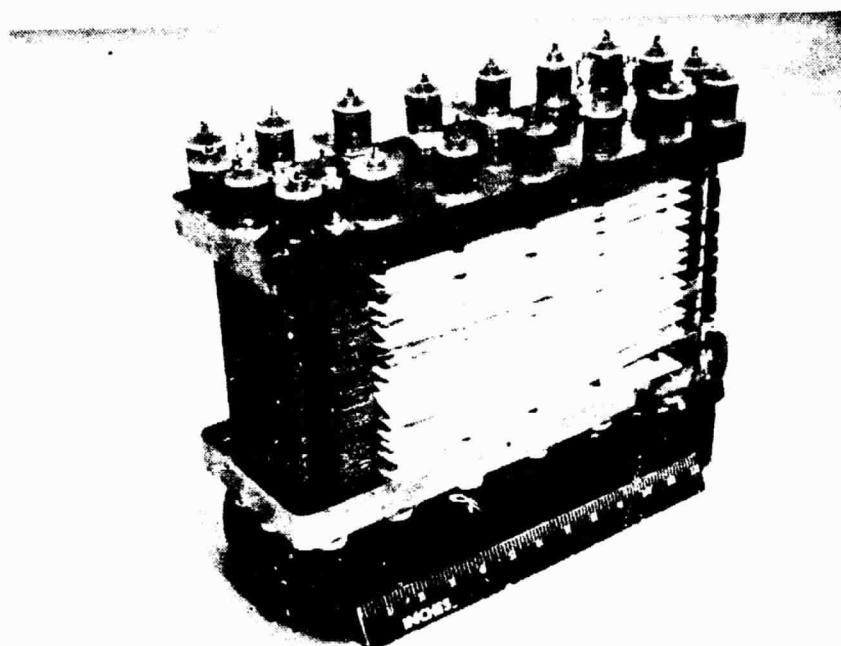
Passive water removal operation eliminates the requirement for a dynamic hydrogen pump water separator thereby allowing a powerplant design with reduced weight, lower parasite power, and a potential for higher reliability and extended endurance. The lightweight fuel cell powerplant design was based upon the requirements of advanced space missions such as Space Tug and Orbital Transfer Vehicle.

The Marshall program culminated in the fabrication of a 24-cell lightweight power section, Figure 32, which has completed a 2000-hour performance demonstration test under the Lewis Research Center Program (reference 1).



(WCN-6336)

Figure 31. Lightweight 3.5 kW Fuel Cell Powerplant



(WCN-7669)

Figure 32. Lightweight Fuel Cell Power Section

Under the MSFC program, over 8,800 hours of endurance testing of two-cell modules, the basic repeating unit of the power section, was completed. These tests confirmed that the lightweight cell design will:

- o Satisfy the 2,500-hour voltage requirement of the Lightweight Fuel Cell Powerplant Design
- o Operate with propellant purity reactants with no significant impact upon cell performance.

A complete summary of the work completed under the Marshall Space Flight Center program is presented in reference 3.

Technology Background

UTC has been conducting an alkaline fuel cell technology advancement program since 1971 under the direction of the Lewis Research Center. This continuing program has identified cell components and a low weight cell design with increased performance and extended life.

- o Developed a lightweight passive water removal cell design with a specific weight of 4 lbs/kW (1.89 kg/kW) compared to the PC17C cell design specific weight of 8 lbs/kW (3.69 kg/kW).
- o Accumulated over 138,000 cell-hours of operation with lightweight passive water removal cell design with one cell operating continuously for 10,021 hours and another cell operating at a current density of 200 Amps/Ft² (215.3 mA/cm²) for 6,680 hours.
- o Demonstrated the increased cell performance and improved long-life stability of the gold-platinum catalyst cathode.
- o Demonstrated the long-life performance stability of the platinum-on-carbon anode catalyst configuration.
- o Confirmed the ability of the alkaline fuel cell to operate in a cyclical mode, representative of a fuel cell-electrolysis cell energy storage system.
- o Identified potassium titanate as a candidate matrix material with the potential to extend cell life.

The work accomplished under the Lewis Research Center program has been reported in references 1 through 10.

REFERENCES

REFERENCES

1. Martin, R. E., "Advanced Technology Lightweight Fuel Cell Program, Final Report", United Technologies Corporation, Power Systems Division, FCR-3045, NASA CR-165417, 18 August 1981.
2. Martin, R. E., "Advanced Technology Lightweight Fuel Cell Program, Final Report", United Technologies Corporation, Power Systems Division, FCR-1657, NASA CR-159807, 4 March 1980.
3. Martin, R. E., "Advanced Technology Lightweight Fuel Cell Powerplant Components Program, Final Report", United Technologies Corporation, Power Systems Division, FCR-1656, 22 February 1980.
4. Martin, R. E., "Advanced Technology Lightweight Fuel Cell Program, Final Report", United Technologies Corporation, Power Systems Division, FCR-1017, NASA CR-159653, September 1979.
5. Gitlow B., Bell, W. F., and Martin , R. E., "Strip Cell Test and Evaluation Program - Final Report", United Technologies Corporation, Power Systems Division, FCR-0945, NASA CR-159652; September 1979.
6. Gitlow B., Meyer, A. P., Bell, W. F., and Martin, R. E., "Development of Advanced Fuel Cell System - Final Report," United Technologies Corporation, Power Systems Division, FCR-0398, NASA CR-159443; June 1976.
7. Meyer, A. P., and Bell, W. F., "Development of Advanced Fuel Cell System (Phase IV) - Final Report", United Technologies Corporation, Power Systems Division, FCR-0165, NASA CR-135030, January 1976.
8. Handley, L. M., Meyer, A. P., Bell, W. F., "Development of Advanced Fuel Cell System (Phase III) - Final Report", United Aircraft Corporation, Pratt & Whitney Aircraft Division PWA-5201, NASA CR-134818, January 1975.
9. Handley, L. M., Meyer, A. P., Bell, W. F., "Development of Advanced Fuel Cell System (Phase II) - Final Report", Pratt & Whitney Aircraft Division PWA-4984, NASA CR-134721.
10. Grevstad, P. E., "Development of Advanced Fuel Cell System" - Final Report, Pratt & Whitney Aircraft, PWA-4542, NASA CR-121136.
11. Trout, J. Barry, "Energy Storage for Low Earth Orbit Operations At High Power", Lyndon B. Johnson Space Center, Houston, Texas.
12. Martin, R. E., Reid, M. A., and Schubert, F. H., "Alkaline Regenerative Fuel Cell Systems for Energy Storage," 819041, 16th IECEC, Atlanta, GA., 9-14 August 1981.